CRANFIELD UNIVERSITY

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ABSTRACT

Competition in the global economic scenario has led to the use of simulation in many areas such as manufacturing, health systems, military systems and transportation. With the importance of simulation in supporting decision making and operations, model building has been recognised as one of the crucial steps in simulation studies. However, model building is not as easy as it may seem. It can be time-consuming and expensive, and requires special training, skills and experience. This research, therefore, aims to investigate a new method to rapidly build a simulation model based on the classification of problems in assembly lines using a cladistics technique and template approach.

Three objectives were established in order to achieve the aim and a four-stage research programme was developed according to these objectives. The first stage starts by developing a thorough understanding of and collecting typical problems in assembly lines. The next stage formulates the classification of problems and the main deliverable is a cladogram, a tree structure that can be used to represent the evolution of problems and their characteristics. The third stage focuses on the development of a proof-of-concept prototype based on an established classification and template approach. The prototype helps users to develop a model by providing the physical elements and specific elements required for the performance measures analysis. The prototype is then tested and validated in the final stage. The results show that the prototype developed can help to rapidly build a simulation model and reduce model development time.

Keywords: Model building, simulation, cladistics, template

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GLOSSARY OF TERMS

ALB(P)	Assembly line balancing (problem)
AMHS	Automated material handling system
CBR	Case-based reasoning
CI	Consistency index
COTS	Commercial-off-the-shelf-software
DES	Discrete-event simulation
DFT	Demand flow technology
DLL	Dynamic link library
DNA	Deoxyribonucleic acid
ERP	Enterprise resource planning
GAs	Genetic algorithms
GUI	Graphical user interface
IGES	Initial graphics exchange specification
ILP	Inductive logic programming
MTBF	Mean time between failures
MTTF	Mean time to failure
MWC	Maritime warfare centre
NJ	Neighbour joining
NN	Neural network

OTU	Operational taxonomic unit
PTO	Power train operations
RI	Retention index
RI	Rule induction
SMEs	Small and medium sized enterprises
UPGMA	Unweighted pair-group method with arithmetic mean
VB	Visual basic
VBA	Visual basic for applications
WIP	Work-in-progress
2D	Two-dimensional

1 INTRODUCTION

This chapter addresses the overview of the thesis. It begins with the key points that have prompted this research and its background (Section 1.1). Section 1.2 focuses on the industrial context of this research. Section 1.3 shows that assembly lines play even more of a role as one of the important systems in manufacturing activities. This is followed then by a summary of the aim, objectives and research programme (Section 1.4). Finally, an outline of each chapter that constitutes the structure of this thesis is presented in Section 1.5.

1.1 Overview of research background

The assembly line is a flow-oriented manufacturing system composed of a series of stations. The workpieces are transferred from one station to another by material transfer devices such as conveyor belt, roller conveyor, skate conveyor or human mover. Assembly lines are commonly designed to reduce the cost for mass production of standardised products (single type of product). Apart from that, assembly lines also have gained importance in low volume production of customised products (Becker and Scholl, 2006). In some cases, an automated production line is used if the volumes of products needing to be manufactured are particularly high. In this situation, the total workload can be divided into separate tasks and assigned to individual stations.

In many cases, assembly line balancing problems arise when distribution of the total workload is not well balanced along the line. This can happen during the configuring or reconfiguring of assembly lines. That is why the configuration of a production system needs to be designed or redesigned carefully in order to provide a well-balanced assembly line so that the system works efficiently. However, it is important to point out that effective design of production systems is generally not as easy as expected. It requires a lot of experience, knowledge and skills, and includes time-consuming and costly activities. From an economic point of view, assembly lines usually consist of expensive pieces of equipment and require large capital investments (Becker and Scholl, 2006; Masood, 2006).

Levels of financial investment can be immense and poor decisions can be detrimental. Thus, cost and profit related objectives should be considered very carefully.

Therefore, one of the most useful and worthwhile tools for the planning, design, and monitoring of complex system is simulation. Simulation can be defined as "the process of designing a model of a real system and conducting experiments with this model for the purpose of either understanding the behaviour of the system and/or evaluating various strategies for the operation of the system" (Shannon, 1992).

Since simulation can be one of the tools available to support the decision making in manufacturing systems, especially assembly lines, model building is becoming one of the critical factors in providing the effective design of complex systems, manufacturing activities and technology. However, a few issues have been raised regarding the implementation of simulation modelling, such as: model building is a complex process; simulation tools are not as easy to use as expected; simulation tools are expensive; and, model building is time-consuming.

This research, therefore, addresses a new approach to facilitate model building so as to reduce the learning curve of simulation studies and to reduce the number of issues, as mentioned above. Generally, there are a couple of options available, one of which is developing a new simulation application or tool. Nevertheless, this option has not been taken into account. Instead, this research is concerned with investigating a new approach to facilitate users to develop a simulation model which consists of a physical layout and the performance measures of problems in assembly lines using a template approach and evolutionary analysis technique.

This research is part of the EPSRC-funded project entitled An Evolutionary Approach to Rapid Development of Simulation Models (grant number EP/E037631/1). This project is working on investigating a new method to rapidly build simulation models using a template and model pattern. Reduction in model development time can have a significant impact on simulation implementation. Apart from that, the uptake of simulation modelling techniques can be improved within industries, especially in the manufacturing sector.

1.2 Industrial context

Most manufacturers, regardless of products, share a common set of problems such as planning and optimising plant capacity, minimising inventory cost, minimising and eliminating bottlenecks in production system, coordinating resources with current demand, configuration of process planning with plant layout and scheduling of tasks through the plant. Current market trends require a wider product variety, fast delivery, high quality of products, excellent after sales services and reduced cost, which put more pressure on devising efficient and innovative manufacturing systems. Designing innovative manufacturing systems, especially assembly lines, requires a lot of time, is a costly activity and is difficult to be implemented due to the complexity of products to be manufactured, processes involved, etc. Configuration of a new design or reconfiguration from the existing design of the assembly lines could have a significant impact on the manufacturers due to the difficulties of getting early visibility of production costs and reliable process times. Poor system design and configuration of assembly lines can be catastrophic to the whole production and business due to negative implications on total operation cost and profit. In other words, design or configuration of layout, equipment, process or operation, labour, etc. are crucial to the level of financial investment. An investigation should, therefore, be carried out to identify appropriate methods, tools or techniques to overcome these established problems.

1.3 Why assembly lines?

The assembly line is a common system and has gained an important position in manufacturing activities. It has been applied widely in many industries including automotive, food and beverages, electrical/electronics, etc. The assembly line itself is a complex system consisting of many influencing factors such as scheduling of tasks, equipment, processes etc. The assembly line is developed based on a new design from scratch or by modifying the existing production line. The process of configuring or reconfiguring the assembly lines requires much time, skills, knowledge and costly activities. Pappert et al. (2010) describe how the planning and scheduling of resources, especially in really heavy machine assembly line production systems scenarios, are complex and very hard to be solved using classical scheduling methods. In addition, optimising the resource scheduling, such as workers, transportation equipment, assignment of tasks and storage cost, is not as easy as expected. Jia et al. (2011) state that the process of planning and optimising of assembly lines, which include sub-assembly sequencing problems, assembly process planning and assembly production line layout planning, is very complex. Thus, computer simulation with dynamic planning of production lines and virtual manufacturing technology has been used to analyse and evaluate the capability of the lines.

In the area of semiconductor assembly lines, Wang et al. (2011b) report that scheduling of assembly lines becomes more complicated and challenging due to the complexity of products, which themselves involve hundreds of pieces of devices and events. Poor scheduling of assembly lines affects the efficiency and productivity of the whole system. Chang et al. (2011) also agree that process flows of machine parts in the aerospace industry are becoming more complicated and complex. Scheduling of part fabrication and aircraft assembly will take more time due to bottleneck problems on the shop floor of the aerospace machine shop, especially machinery breakdowns. Moreover, the aerospace industry can be described as a capital intensive, technique intensive and labour intensive industry which requires a full monitoring of the performance of the machine shop in order to produce high quality aircraft parts.

1.4 Summary of research aim, objectives and programme

The aim of this thesis is to investigate a new method to facilitate model building in order to reduce model development time by using a cladistics technique and template approach. To do this, the research objectives have been defined as follows:

- To establish an understanding of typical problems in manufacturing systems (especially in assembly lines).
- To apply a cladistics technique to problems (sample data) established for classification and evolutionary analysis.
- To develop a proof-of-concept prototype which can rapidly build a simulation model based on a template and reusable elements (modules) approach.

1.5 Thesis structure

The structure of this thesis consists of eight chapters; a brief description for each of them is shown below:

Chapter 2 introduces the problem statements of this research and describes the literature review that has been carried out.

Chapter 3 defines the research methodology and research programme.

Chapter 4 addresses a collection of problems in assembly lines.

Chapter 5 discusses the fundamentals of cladistics and cladogram development.

Chapter 6 presents the development of a rapid model generator.

Chapter 7 shows the testing and validation carried out for this research.

Chapter 8 focuses on the discussion and conclusions of this research.

2 LITERATURE REVIEW

The aim of this chapter is to develop an understanding regarding the importance of model building in simulation and the challenges faced in manufacturing systems' design or redesign. This chapter is organised as follows: Section 2.1 presents the introduction of this chapter which covers the importance of simulation modelling from both an industrial and academic perspective. The section addresses the benefits of simulation, advantages of simulation tools, implementation of simulation in industries, barriers in model building and previous research works in speeding up model building. Section 2.2 shows the gaps in the knowledge and the research opportunities available in facilitating model building so as to reduce model development time. Section 2.3 addresses the need for a new method in order to build a simulation model rapidly. Section 2.4 presents a summary of the chapter.

2.1 Background

2.1.1 Simulation and its purposes

Discrete-event simulation, or simulation as it is more popularly known, is one of the most useful and worthwhile tools that industrialists can apply during manufacturing systems' design and redesign. Suri and Tomsicek (1988) report that the benefits of rapid simulation modelling and analysis can have a significant impact on manufacturing activities, especially in the present trend of a competitive manufacturing environment. A simulation technique can be seen as one of the essential tools for the design or redesign of operations in manufacturing systems.

The Oxford English Dictionary defines simulation as:

"*The technique of imitating the behaviour of some situation or system (economic, mechanical, etc.) by means of an analogous model, situation, or apparatus, either to gain information more conveniently or to train personnel.*"

It also defines the general term of a model as:

"*A simplified or idealised description of a system, situation, or process, often in mathematical terms, devised to facilitate calculations and predictions.*"

In addition, Banks (2000) states that "simulation is the imitation of the operation of a real-world process or system over time. Simulation involves the generation of an artificial history of the system, and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system that is represented. Simulation is an indispensable problem solving methodology for the solution of many real-world problems. Simulation is used to describe and analyse the behaviour of a system, ask "what if" questions about the real system, and aid in the design of real systems. Both existing and conceptual systems can be modelled with simulation."

Shannon (1992) reports that "simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose of either understanding the behaviour of the system and/or evaluating various strategies for the operation of the system." Simulation includes both the construction of the model and the experimental use of the model for studying and monitoring a problem. In addition, Pollacia (1989) defines simulation as "the process of modelling a proposed or real dynamic system and observing its behaviour over time."

Many researchers have reported that 'simulation technique' is one of the major options available in assisting the re-engineering process and to boost business performance (Johansson and Jörgensen, 2001; Johansson and Kaiser, 2002; Williams et al., 2001). In addition, Currie and Hlupic (2000), and Adams et al. (1999) argue that simulation technique has the potential and is beneficial for quality management systems improvement. Shannon (1992) has also listed a few benefits of simulation: i) to identify new information regarding an organisation's policies, operating procedures, organisation's structures, etc. without disrupting the existing operations; ii) to test the new configuration of production systems including design of physical layout, material handling system, etc. before the real implementation is carried out; iii) to identify the root cause factors that influence performance and how those factors interact with each other; iv) to identify any elements that lead to bottleneck problems in the whole system; v) to carry out some experiments which are capable of answering the “what if” questions in different scenarios with limited knowledge and experience. Furthermore, Banks (2000) describes that simulation can be used to simulate a bank’s operation and to carry out performance measures such as waiting time for each customer, idle time percentage, etc. He also emphasises that “simulation is used to describe and analyse the behaviour of a system, ask *what if* questions about the real system, and aid in the design of real systems”. He also lists some advantages and benefits of using simulation: i) to test the proposed design of manufacturing systems without committing resources to acquisition because changes of equipment can be extremely expensive; ii) thorough understanding of any possibilities can be carried out based on a valid simulation model being developed without the expense of and disruption to the real system; iii) identify constraints or root causes of problems established; iv) to assist in developing understanding about how the whole system really operates; v) simulation study is a wise investment because the cost of a change to a system after installation is very expensive; vi) based on aims and objectives established, simulation can be used to identify the specific requirements for the system. Mujtaba (1994), also argues that “modelling and simulation are useful when system prototyping is too costly or time-consuming, seriously disruptive, or simply impossible. They are useful for exploring proposed system changes by providing performance estimates of a proposed system or of an existing system under some projected set of operating conditions. A simulation model or set of models can provide an experimental test bed on which to try out new ideas or concepts, since it is cheaper to experiment in the laboratory than on the real system.” Mujtaba (1994) also added that simulation technique can be applied to enterprise processes to predict the behaviour of an organisation.

McLean (2003) reports that “simulation case studies are conducted to analyse and improve the efficiency and effectiveness of manufacturing organisations, systems, and processes. Studies are designed to solve specific problems and get answers to specific questions. Studies often model some aspect of current operations and validate the effect of some hypothetical change(s) to those operations. The performance of current and proposed systems is evaluated according to some set of metrics. If the simulation shows that sufficient improvements can be expected, then the proposed changes are implemented". Apart from that Standridge (2000) has categorised manufacturing case studies of teaching simulation into four modules: i) basic manufacturing systems of organisation (assembly lines, job shops, etc.); ii) system operations and strategies (flexible manufacturing systems, cellular manufacturing, etc.); iii) material handling systems (conveyors, automated guided vehicle, etc.); iv) supply chain management (inventory systems, logistics planning, etc.). McLean and Leong (2002) describe the main reason for using simulation in manufacturing as being to provide support tools that aid the manufacturing decision making process in many cases, such as market forecast, logistics network, scheduling, plant layout, capital equipment, work force, product mix, line balancing, cost estimation, process validation, process capability, tooling, inventory, material handling and maintenance.

In summary, the benefits of using simulation are huge and most of them are mentioned by many authors (e.g. Banks, 2000; Law and Kelton, 2000; Pegden et al., 1995; Robinson, 1994; Schriber, 1991; Shannon, 1992; Xu, 2006):

i. Simulation can be used to support decision making by executing "what-if" scenario tests in various conditions

ii. To evaluate the performance of existing system under various conditions in a short period of time

iii. To compare the advantages and disadvantages for each system to see which design best meets the objectives

iv. Performing experiments through simulation is quicker and less expensive than using a real system

In addition, a few more advantages of simulation have been given, as listed below (e.g. Chung, 2004; Niu, 2007):

i. To get early visibility of operations of a system

ii. To improve the existing system performance by enhancing resource and operating policies

iii. To identify the root cause of problems without disrupting the actual system

2.1.2 Advantages of simulation tools

Today's highly advanced environment with intensely competitive and challenging market demands places great emphasis on strengthening efficiency, improving strategies and reducing costs. Simulation modelling is used as a successful tool to design and analyse manufacturing systems. Enhancing product design, production systems and production strategies are important issues. In addition, generating efficient simulation models with shorter lead times has become equally important towards winning customers' satisfaction.

Simulation modelling is being widely used in areas such as manufacturing, health, network communications, training, education and military. There are many commercial-off-the-shelf-software (COTS) for simulation in the market. COTS are featured with computer-based graphical animations which represent the behaviour of the manufacturing system being modelled. The available COTS are variants such as general purpose tools, tools specifically designed to model and analyse manufacturing systems, tools for transportation systems, etc. Model building and simulation modelling is synonymous with manufacturing activities because each of them has become one of the primary application areas in simulation environment. Simulation modelling has been used to improve, validate, test and evaluate the designs of a wide range of manufacturing systems. Typically, simulation models are representations of machines, schedules, conveyors, part flows, labours, and then performance predictions of manufacturing systems and facilities in terms of measures will be carried out, such as production volume, manufacturing lead time, machine utilisation, work-in-progress, etc. The simulation tools allow the users, especially modellers, to carry out “what-if” scenarios that are useful to gain a deeper understanding of how a new or alternative manufacturing system will perform before any investments or modifications are made. In this way, the insight provided by the application of simulation helps manufacturers make more effective decisions, resulting in much less risk of failure.

2.1.3 Implementation of simulation technique in industry

Even though the advantages of simulation are huge, the proportion of simulation techniques that have been adopted in manufacturing activities is relatively low (Hlupic, 2000; Melão and Pidd, 2003; Murphy and Perera, 2002; Robinson and Pidd, 1998). There are no remarkable changes to the progression of this trend based on the survey conducted by Hollocks (1992). Tjahjono and Baines (2004) report that around 20% of manufacturers in the East England region have applied simulation techniques as a decision making tool. Although around 40% of them were not aware of the capabilities of simulation tools or even realised how to implement them in the decision making process. This issue has been raised due to four major barriers: i) model building is a complex task; ii) simulation tools are difficult to use; iii) simulation tools are expensive; iv) model building is time-consuming. This situation may become worse because experts in simulation modelling are very few and far between (Bansal, 2002).

Randell (2002) reports that the use of simulation in the Swedish industry is relatively low, as shown in Table 2-1. Respondents were asked whether the simulation had been used frequently in their company and the results were established as follows: i) 60% strongly disagree; ii) 16% somewhat disagree; iii) 7% agree; iv) 1% somewhat agree, v) 4% strongly agree. The results show that 76% of respondents did not use simulation frequently in their company and only 12% used simulation frequently as part of the activities in their company.

Table 2-1 Results of simulation usage in Swedish industry (Randell, 2002)

In our company simulation has	I strongly disagree	I somewhat disagree	I agree	I somewhat agree	I strongly agree
been frequently used	60%	16%	7%	1%	4%
been seriously considered	42%	16%	17%	5%	3%
a solid knowledge base	46%	21%	10%	5%	3%
given us good experiences	51%	15%	10%	5%	2%

In another survey conducted by Hirschberg and Heitmann (1997), the results show that 65% of the respondents are current users of simulation and 21% of them did not use simulation in their business activities as shown in Table 2-2. Based on the statistical results established, the number of companies using simulation will increase in the coming years in Germany because 11% of the respondents are planning to use simulation in their business activities.

Table 2-2 Results of simulation usage in Germany industry (Hirschberg and Heitmann, 1997)

User	Percentage
Current user	65%
Plan to use simulation	11%
Previous user	3%
Not a user	21%

Therefore one of the challenges this research attempts to address is to find an effective way to make the simulation modelling process simple so as to reduce the model development time.

2.1.4 Barriers in model building and simulation

Simulation and model building have been implemented in many areas such as manufacturing, military, transportation, health, etc. There are many benefits and advantages of simulation modelling in improving efficiency, productivity and cost, which is why simulation modelling is important among manufacturers in obtaining an early overview of the production planning that has been made.

Model building is one of the important steps in simulation. Building a model requires a thorough understanding of the established problems, identifying and constructing the elements required, determining the relationships of the elements involved and developing the logics required to link the elements established (Guru and Savory, 2004). It can be seen therefore that model building is not an easy task but is actually very complex. In addition, the process of model building consumes much time and is a costly activity. Table 2-3 shows a list of publications with issues related to model building raised by previous research.

Table 2-3 Issues in model building

Author	Issues in model building
Shannon (1992)	• "Simulation analysis can be a time-consuming and expensive process" • "Model building is an art and requires specialised training. The quality of the analysis depends upon the quality of the model and skill of the modeller. Model building is an art and as such, skill levels of practitioners vary widely"
Banks (2000)	• "Simulation modelling and analysis can be time-consuming and expensive" • "Model building requires special training"
Mujber et al. (2005)	• "The problem with the simulation packages available on the market today, it requires good knowledge about programming and modelling techniques. Also, it is very time- and money-consuming to develop a simulation model for a manufacturing system"
Bansal (2002)	• "The modelling experts are very few and far between" • "Even with the trained modellers the effort to construct a good descriptive or optimisation model is huge, so that most companies are unwilling to spend" • "Then the input data problem, be it static or dynamic, is as time-consuming as the construction and validation of the model itself"
Hollocks (2006)	• "A time-consuming feature of simulation modelling is designing, writing and de-bugging the model's code. From the earliest days of simulation, there has been interest in creating the means to make this more rapid and more reliable... "
Xu (2006)	• "A high level of precision is required to collect the information implemented in the model, which is directly related to the accuracy of the model results. If the simulation model does not correspond to the reality, the results from the simulation cannot be valid, or can even lead to wrong decisions" • "It consumes a huge quantity of time, human resource and technical, to build a model; therefore, creation of a simulation model is expensive"

Robinson and Bhatia (1995) and Trybula (1994) argue that the model development phase can take up almost 10% to 40% of the total simulation time. Also, Willemain (1995) reports that model building time can take up to almost

60% of the total simulation time as a consequence of developing a thorough understanding and structure of the model. In addition, Mujtaba (1994) comments "if the relationships that compose the model are simple enough, it may be possible to use mathematical methods (such as algebra, calculus, or probability theory) to obtain exact information on questions of interest; this is called an analytic solution. However, most real-world systems are too complex to allow realistic models to be evaluated analytically, and these models must be studied by means of simulation." Yapa et al. (2005) also argue that two major reasons for the lengthiness of the model building process are the lack of understanding of the system being studied and the difficulty in programming. They also argue that improving programming efficiency does not guarantee that the model developed in a shorter period of time is the model which represents the actual physical model.

Model building requires modellers to fully understand the problems involved, develop the model which consists of physical and performance measures elements, identify the relationships between the elements, and develop the logics to link the elements established. Although simulation is one of the most effective techniques in system modelling and analysis, sometimes it still does not provide a precise and useful result. The main reasons for this are: i) lack of skills among the modellers; ii) model formulation. Model formulation is one of the key steps in simulation study which requires the modellers to understand the problems involved, visualising and assembling the required elements, and identifying the relationships between the elements established based on an actual system. Good results from the simulation study are highly dependent on the modeller's skill and knowledge, a good understanding of elements required for each problem to be tackled, and relationships between variables and parameters established (Guru and Savory, 2004). Robinson (1999) argues that simulation studies fail to produce useful results due to the poor modelling skills of the modeller in designing a good conceptual model that represents the real system's problem under study and correctly identifies the required level of details including specific variables or parameters. Robinson (1999) also describes three key elements that have been outlined during the modelling process which contribute to simulation inaccuracy: i) modelling process requires modellers to understand the problem to be solved; ii) development of conceptual model; iii) coding required of a computer model. In addition, “a time-consuming feature of simulation modelling is designing, writing and de-bugging the model’s code. From the earliest days of simulation, there had been interest in creating the means to make this more rapid and more reliable.” (Hollocks, 2006).

An observation was conducted by Willemain (1995) on how experts formulate problems especially for simulation purposes. The research found that the expert spent 59% of their time on model structure (actual model building), 16% on model assessment (the model’s correctness), 14% on problem context (problem definition), 9% on model realisation (estimating parameters and how to make sure the model fits the data), and 2% on model implementation (reviewing the model’s output). As a result, the most time-consuming questions for model structure issues being addressed by the modellers when conducting a simulation study are listed below:

- “What are the (system) variables?”
- “What are the relationships among the (system) variables?”
- “What kind of model should I make?”
- “What process would I follow to make the model?”
- “How should I analyse the data to understand the problem?”
- “What are the steps in any model that are defined as procedure?”

The above findings show that 59% of the model development time was spent solely on developing understanding and the structure of the model. In addition, Tjahjono and Baines (2004) have found that there has been an increasing trend towards the use of simulation techniques by people who are neither experienced nor experts in simulation and modelling. For that reason, actions need to be taken to make simulation tools easier to use, which in turn will speed up model building.

As a summary, model building is quite a complex task, extremely time-consuming and a costly activity, making implementation difficult (Albores et al., 2007; Bell et al., 2006; Guru and Savory, 2004; Kibira and McLean, 2002; Mackulak et al., 1998; Mertins et al., 2000; Mukkamala et al., 2003b; Song et al., 2006). Figure 2-1 summarises a few challenges or drawbacks that need to be taken into consideration before implementing simulation modelling.

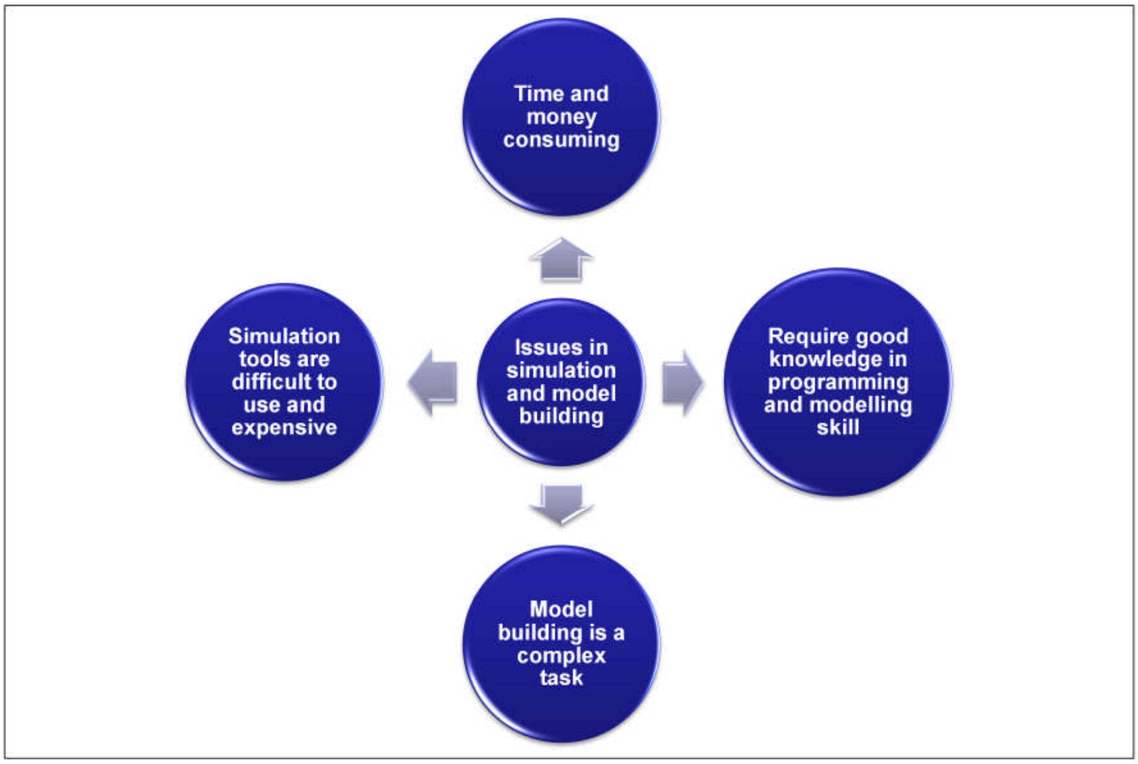

Figure 2-1 Issues in simulation and model building

2.2 Previous research in rapid model building

For the reasons and issues stated above, efforts have been made by previous studies to make simulation tools easier to use, which in turn will speed up model building. These include the use of secondary user interface, rationalisation of data format (easing the data collection efforts), data driven simulation methodology as well as model building using templates.

2.2.1 The use of secondary user interface

One of the options available is the creation of a secondary user interface for data input/output in order to assist the decision making process. Some of the previous research works demonstrate how the commercial-off-the-shelf-software (COTS) for simulation can be linked to other software or systems. This includes the integration of COTS, Witness, and the expert systems package (XpertRule) through a Visual Basic interface, in order to provide a means of representing a decision making process (Robinson et al., 2003). In this research, a rule-based expert system has been developed to represent the decision to allocate trucks to lanes in the loading bay. Whitman et al. (1998) describe the usefulness of the integration of a web-based interface with discrete-event simulation tools. This research is carried out to develop a simulation environment for supply chain design so that the supplier, especially small and medium sized enterprises (SMEs), can execute the simulation to determine the preset parameters and their portion of the supply chain. Since COTS are very useful in assisting the decision making process but many SMEs are unable to afford the start-up cost. It is therefore, the web-based application developed using Witness and Visual Basic Script that is capable of facilitating enterprises in the supply chain.

In addition, McKenna and Little (2000) have addressed the importance of developing operational tactics and procedures for the Royal Navy's Maritime Warfare Centre (MWC) using simulation technique. The application, which consists of a user interface, has been developed using Visual Basic for Application in an Excel spreadsheet. The purpose of this developed application is to optimise the capability of the fleet's platforms, sensors and weapon systems. The main reasons for using Microsoft Excel are: i) it is widely available and familiar to all likely users; ii) to reduce cost. Even though the benefits of the Excel spreadsheet are huge, some drawbacks have been noted by McKenna and Little (2000): i) "Excel does not provide graphics, only graphs. Although there are a large number of standard graphs that can be plotted, each individual graph is very constrained in how data can be plotted. For example, "a bearingtime graph that can “wrap” around at 0/360 degrees has so far proved beyond us”; ii) “The programming language behind Excel – Visual Basic for Applications (VBA) – is an interpreted language, which means that algorithms coded up in VBA might execute slowly. This can be overcome by coding them separately and providing them in DLLs”; iii) “There is the assumption that all potential users of the simulation will have access to Excel and preferably a particular version – some versions of Excel have not been completely backward compatible”.

Ladbrook and Januszczak (2001) describe the improvements in visual and interactive capabilities in simulation modelling, allowing the engineers to directly be involved in model development, which includes identifying the functionality of the model, data collection, validation and running experiments. Although the benefits of simulation are huge, simulation and model building cycle time, which includes defining the main problem, data collection and results presentation, are time-consuming processes and have a high cost. Some of the elements that have been chosen to assist Ford’s Power Train Operations (PTO) simulation environment and especially their engineers are: i) the simplistic construction of the model; ii) the method of data input and of listing the details. These include the concept of a menu driven user interface and embedded logic.

In addition, Otamendi et al. (2008) have developed a visualisation tool using Java-based platform and Visual Basic software to assist airport management to properly schedule resources in terms of shifts, requirement levels, weekly or daily assignments and on-line control. This research was also carried out to reduce the model development time by providing *ad hoc* logic statements. Otamendi et al. (2008) also make a few statements regarding commercial simulation tools and model building: i) commercial simulation tools such as Witness and Arena may not be user-friendly enough; ii) commercial simulation tools are expensive; iii) changes in the logic of the system may need complex changes in the model; iv) the connection between model visualisation and model logic is not easy to establish in commercial simulation tools. It is therefore the development of the visualisation tool in their research that is capable of managing the shifts of personnel and levels of material resources efficiently.

Mujber et al. (2005) have implemented simulation modelling on the shop floor and in process planning. Since commercial simulation tools require a good knowledge of programming and model building, a user-friendly graphical user interface has been developed so that new users of simulation or administration, i.e. who do not have experience in simulation modelling, can use this application easily. In addition, developing a simulation model in manufacturing systems is quite difficult and a very time-consuming process. The application was developed using Excel spreadsheet, Visual Basic script and Witness which provide non-expert users with the flexibility to develop a simulation model of real shop floor activities dynamically.

Salzwedel et al. (2007) also developed a hierarchical graphical user interface and standardised building block for rapid simulation modelling of hospital processes based on clinical pathways for acute coronary syndromes, especially in cancer treatment centres. The hospital processes include function of hospital architecture, the availability of quantity shared resources such as beds, server shared resources such as physicians and nurses, and proper scheduling of treatment events. The aims of their research are: i) to minimise cost of treatment; ii) to improve quality of care; iii) to attract more patients; iv) to become more competitive. The model of the hospital processes was developed using MLDesigner. The results show that standardised building blocks can significantly reduce model development times. Therefore, large reductions in cumulative patient treatment times could be realised, based on established standardised building blocks.

2.2.2 Data driven simulation methodology

Wang et al. (2011a) have developed a data driven simulation methodology that provides a “rapid prototyping” capability to automatically model a production system and rapidly modify, analyse and remodel the model based on dynamic requirements and real time information. Wang et al. (2011a) also define data driven as “a method that allows a user to create and run a simulation model without the need to do any programming”. In addition, data driven simulation can be described as “a simulation model that can be completely parameterised by providing data through a set of data forms, tables, spreadsheets, or templates and is designed specifically for modelling an identified set of systems” (McLean et al., 2002; Wang et al., 2011a). The methodology developed in this research has been applied to automotive assembly lines with material handling systems. The Arena simulation tool is used to develop the simulation modules for assembly lines and material handling systems. The methodology developed is capable of improving the responsiveness and flexibility of the production lines effectively.

Lee et al. (2000) developed a conceptual framework in rapidly generating simulation models of the shop floor from process plans and resource configurations. However, modelling a shop floor control system using simulation technique is not as easy as expected and requires costly efforts. Thus, this research addresses a conceptual framework to generate a Witness simulation model automatically from graph-based process plans and resource configurations. The framework established is capable of rapidly building a simulation model and conducting performance measures effectively, such as bottleneck identification, work-in-progress, deadlock, utilisation of resources and throughput times.

Tjahjono and Fernández (2008) proposed a methodology that is very useful in helping manufacturing engineers when executing the simulation study of car engine assembly lines. A user interface has been developed which consists of Excel spreadsheet and Witness software. The spreadsheet automatically generates the simulation codes that can be run by Witness. The user interface can significantly speed up model building by facilitating users to develop the model, especially those who are not experts in simulation, and to build and modify complex assembly lines consisting of machines, conveyors, labourers, etc. Son and Wysk (2001) also addressed a structure and architecture for automatic simulation model building on shop floor using Arena. The simulation code generated, based on a shop floor resource model and shop floor control model, can be used for system analysis and to control manufacturing systems.

2.2.3 Facilitating input/output data collection

In addition, Robertson and Perera (2001, 2002) argue that data collection is the most crucial stage in the model building process. The data collection process and model development can take up to 40% of the total time of the entire project in reality (Trybula, 1994). There are a few difficulties or issues in data collection: i) data accuracy, reliability and validity; ii) data sources; iii) data capture; iv) data duplication; v) timeliness of data. The acquisition of data in terms of timeliness and accuracy is very important to the analysis and model development. In addition, the model development process will be delayed when required data is unavailable. Therefore, a methodology has been proposed to develop an automated interface between simulation tools and organisations' corporate business systems, especially the Enterprise Resource Planning (ERP) system.

Wang et al. (2011a) argue that rapidly accessible production data are beneficial for real time simulation and real time control of the shop floor. Moreover, manual data collection and entry are error prone and time-consuming processes. Ingemansson et al. (2005) presented a methodology with a combination of automatic data collection and discrete-event simulation (DES) to reduce bottlenecks in a manufacturing system. Three main advantages of an automatic data collection and DES have been addressed in their study: i) "objectiveness of data"; ii) "accuracy of time measurement"; iii) "the opportunity to classify production disturbances in relevant categories".

2.2.4 The use of template

The challenge of this research can be summarised by the following question:

"How could the manufacturing modeling and simulation process be improved?"
(McLean and Leong, 2002)

“Today simulation analysts typically code their models from scratch and build custom data translators to import required data. A better solution would be to simplify the process through modularisation, i.e., the creation of re-usable simulation model building blocks. Simulations would be constructed by assembling or configuring, modular building blocks. Similarly, neutral interface formats for transferring data between simulation and other manufacturing applications are also needed. Data would ultimately be imported directly into the simulators without translation using standard data input formats” (McLean and Leong, 2002).

Apart from that, a template can be defined as a set of prebuilt, ready to use, modelling objects, modules, or models of common simulation situations (Mukkamala et al., 2003b). By using templates, model development time can theoretically be reduced because of the reusability of modelling components, model subsystems or even similar models. Templates may have a number of modules and model parameters, and these parameters can be available or unavailable in order to fit the templates to the system under study (Guru and Savory, 2004; Thesen, 1990). Templates typically have a number of characteristics including: independence, reusability, replace ability, adaptability, effective user interfaces, internal structure encapsulation (Mukkamala et al., 2003b). Table 2-4 shows some previous research works that use the template approach to speed up model development time.

Table 2-4 Related works in the template based approach

Author	Area of DES
Generic simulation models of reusable launch vehicle (Steele et al., 2002)	Reusable launch vehicle (space shuttle)
Effective simulation model reuse : A case study for AMHS modeling (Mackulak et al., 1998)	Automated material handling system
Simulation in a box: Generic reusable maintenance model (Brown and Powers, 2000)	Operation and maintenance component of air force wing
The use of template-based methodology in the simulation of a new cargo track from Rotterdam Harbour to Germany (Pater and Teunisse, 1997)	Cargo track capacity
Automatic simulation model generation for simulation-based, real-time shop floor control (Son and Wysk, 2001)	Shop floor control
Simulation-based shop floor control: formal model, model generation and control interface (Son et al., 2003b)	Shop floor control
Integrating schedulability analysis with UML-RT (Gao et al., 2006)	Schedulability analysis

Mackulak et al. (1998) argue that the effective approach for model creation is to reuse an existing generic model which can be easily configured for individual projects through flexible interface especially in an automated material handling system (AMHS). As a consequence, this will reduce model development time as well as increase simulation accuracy. Their research states that any simulation model contains some level of attraction. Therefore, the cost of modelling is minimised when an appropriate level of detail is included. On the other hand, the generic/specific concept investigates the ability to define models that are applicable to a wide range of situations. Mackulak et al. (1998) also describe how a model is referred to as generic when it is applicable to some large set of system and is sufficiently accurate to distinguish between critical performance criteria. The model becomes specific when the data for a particular system are loaded. This is similar to the approach used in some of the early simulation tools such as Witness, SimFactory and Arena.

The process of creating a generic model begins with a layout diagram developed by a design engineer. The design is translated from CAD into IGES format so that it can be directly input to the simulation model. Implementation of reusable models is carried out by the use of spreadsheets for data input. Validation is performed to ensure that the model logic performs identically to the control logic of an actual material handling system. As a result, model building has been reduced from six weeks to less than one week with a high accuracy of model specification.

Steele et al. (2002) have addressed a method to construct a simulation model that is generic to all the systems in a given domain. There are two conditions for conducting a simulation study: first, the details of the system are unknown because it is early in its design phase and second, two or more competing systems are to be compared. The main constraints in developing simulation models are time and budget. One consideration regarding the development of generic simulation is the ‘domain at hand’ because a more general model is more difficult to construct and validate. Secondly, time required for the simulation study should be reduced because the model only needs to be populated with data from various systems and not constructed from scratch.

The research in the area of generic simulation models are developing models applicable to more than one system and simulation models that are uniquely composed from a library of previously developed modules are generic at the module level only but more specific to the system under study. One of the risks in developing such models is the steady growth of requirement. The approaches to handling this situation are: constricting the scope of study to a manageable size, monitoring the requisite level of detail, focusing on important factors, simplifying input and having user-friendly output. The steps in constructing a simulation models are as follows: i) select the domain of interest (problem to be solved); ii) draw a conceptual level diagram of a generic system in the domain; iii) identify the constructs (things that flow in the system, action and equipment to perform the actions); iv) translate the conceptual model into a computer simulation model.

El Haouzi and Thomas (2005) and El Haouzi et al. (2008) also propose that a framework to develop a library consists of generic simulation components so as to generate specific models automatically from the modular simulation model. The framework is used to evaluate the impact of operators' flexibility induced by demand flow technology (DFT). In their research, the simulation model is structured based on two principles: i) "the separation of physical, information and control elements"; ii) "the distinction between processes that are purely decisional or physical and the mixed processes that belong to physical and decisional systems". The generic components have been developed using Arena and Visual Basic software.

In addition, Hu and An (2011) have addressed a new approach to generating simulation models for manufacturing systems, especially in an unstable manufacturing environment, i.e. the case of one company that produces booster cable in China. The specific models are generated based on generic models by retrieving the data from manufacturing information systems. The objective of their research is to maximise the product capacity and to increase the efficiency of the manufacturing systems. The results show that users can rapidly modify some of the elements in the manufacturing systems, such as number of workstations, processing time, buffer capacity and controlling method, to remodel the existing manufacturing systems. The application developed can help the users to rapidly respond to the change of manufacturing activities.

Brown and Powers (2000) have addressed the importance of designing a generic model and evaluating the impact of maintenance functions on the operations of an air force wing, so as to apply the same concepts to other military and commercial maintenance operations. The concept of the generic model has been proposed because developing a simulation model from scratch is a time-consuming process. Therefore, this research which is called the Scalable Integration Model for Objective Resource Capability Evaluations or SIM-FORCE, aims “to ensure that the basic model is generic enough to support a broad range of applications including commercial applications”. In addition, this application can reduce the model development time so as to assist the decision making process. This application has been developed using Arena, Excel spreadsheet and Visual Basic for Applications (VBA).

Pater and Teunisse (1997) propose the use of a template in the simulation of a cargo track. They define a template as “a collection of user-defined, re-usable modelling building blocks. Building blocks are created by programming their functionality interface, animation and performance indicators in a suitable simulation environment”. A few advantages of the template have been quoted by them: i) “it speeds up the time to build a model significantly because concepts and functionality can be more easily re-used”; ii) “there is a separation between design and implementation; the needed complexity, once built and tested, is hidden from the user of the template, making it easier for that user to concentrate on functional instead of technical problems”; iii) “verification of models is easier because of easier verification of the separate building blocks”; iv) “experimentation is much easier because either parameters are changed on easy-to-find spots or high-level building blocks are added instead of changing low-level codes”; v) “it becomes possible for many more people to build an actual model with a template without the need for extensive training in simulation or a specific simulation environment”; vi) “the use of a template reduces the risk of having too much detail in the model because of the dedicated functionality of the template”. The model components in a library were used to study if the capacity of the railway meets its requirements.

Another automatic simulation model generator for a shop floor control system was conducted by Son et al. (2000). Their research has proposed the development of neutral libraries of simulation components and model templates.

The aim is to reduce the complexity of simulation modelling and analysis. The model builder has been developed using Visual Basic (VB) and Microsoft Access. The templates were generated from ProModel simulation tools and these templates can be accessed by the model builder.

In addition, Son and Wysk (2001) and Son et al. (2003a) have presented the structure and architecture of automatic simulation model generation for shop floor control using the template approach. The shop floor resource model (static information for the simulation model) and shop floor control model (dynamic information required by the simulation model) have been used to generate the simulation model code. Their research has addressed a few constraints regarding model building: i) simulation modelling on shop floor control requires high levels of system detail; ii) modellers must have skills and knowledge in using simulation tools or packages and statistical methods; iii) simulation modelling is a time-consuming process – even experienced simulation modellers will take a lot of time to model a complicated system. Their research is carried out to investigate whether a simulation model can be automatically generated from existing entities. The automatic simulation model generation has been developed using Arena and Visual Basic. Apart from that most of the shop floor components used in the model generator development are buffer, robot and machine. As a result, this application is capable of generating six samples of manufacturing systems within two to five minutes.

The benefits of using templates are huge, which in turn will speed up model building, and most of them are mentioned by many authors. This includes the development of a template based simulator to analyse a material handling system on a manufacturing shop floor (Thesen, 1990), simulation templates for tower crane operations for the purpose of reducing the model complexity (Appleton et al., 2002), development of templates for the automated assembly of printed circuit boards (Farrington et al., 1996; Mukkamala et al., 2003a), and development of component based simulation for car engine assembly lines (Winnell and Ladbrook, 2004).

2.3 Justification for research

The previous section shows that a number of research works have promoted the use of templates in simulation model building. Despite the significant number of works that address the advantages of the template approach in model building, the reliability, robustness and generality of the application developed using this approach remains the gap in knowledge that requires further investigation. A thorough review of the literature has revealed the reason for this gap:

- First, the template approach has been implemented and customised to a very specific domain, for example space shuttle, cargo track, shop floor, etc., and was developed to fit within the framework of a particular commercial-off-the-shelf-software (COTS). The significant impact of this issue is that additional work is required to customise the existing template in order to fit the elements of the templates within the context of study. This situation, therefore, requires more expertise, programming skills and knowledge in using particular simulation tools or programming language.

- Second, the models generated using templates are limited to regular patterns, for example, assembly lines in a car factory. The assembly lines typically consist of machine, conveyor and buffer. In this situation, a conveyor moves parts to be machined and a buffer is used to store the machined part as work-in-progress (WIP) before the parts are transferred to another machine or exit the system. The "machine-conveyor-buffer" configuration is in fact a template or building block which consists of three physical elements. Due to the regular pattern of the template, it can be duplicated and linked together to construct a complete assembly line.

- The problems being addressed by using simulation can also evolve, depending on the system being modelled. This has happened due to manufacturing systems evolving over time. For example, Ford was once known as a craft manufacturer which then evolved further into a mass manufacturer and then into a lean manufacturer due to market competition, technology requirements, current demands etc. Although templates can be developed and implemented based on similarity of a system's layout, the types of problem being addressed and types of decision making to be made can be completely different. Each problem is unique and requires specific elements to be implemented in the simulation model so that the problems being addressed can be monitored effectively.

2.3.1 The need for a new method to rapidly build a simulation model

Today's highly competitive manufacturing environment gives prominence to the benefits of rapid simulation modelling and analysis in order to improve efficiency and reduce cost. Model building and simulation are being widely used as useful and worthwhile tools to design/redesign and analyse manufacturing systems. This includes designs of a wide range of layout planning and their effects on the whole manufacturing system. Therefore an efficient, rapidly built simulation model with a shorter lead time has become one of the important criteria to improve process planning and customer satisfaction.

The potential of the template approach in speeding up model building is huge and this can be clearly seen in previous works, as described in the previous section. Providing a correct template for simulation modelling is, therefore, very important. The difficulty in providing the most appropriate simulation template for speeding up model building is largely because manufacturing systems, and more importantly their problems and hence the associated types of decision making, are not well categorised or classified.

Previous works in generic template creation for simulation models have been solely based upon physical layouts (e.g. assembly lines, cellular layout) but not necessarily based upon the problems that a simulation study will address. For example, a typical manufacturing problem to be solved using simulation is to identify the bottleneck, which usually leads to the identification of the appropriate buffer locations (and sizes) to overcome this bottleneck. Optimising buffer sizes and locations would also address the problems in the minimisation of WIP. From this example, it is apparent that the goal of a simulation model may evolve from tackling one problem or another. For this reason, a new method of developing simulation model templates is required, allowing simulation models to be generated based upon similarity of problems being addressed and hence the similarity of the decision to be made. Therefore, two models with completely different layouts may share the same model template because they also share similar problems. Apart from that, there must be a reason and special need for using the simulation technique, especially in manufacturing activities. Most simulation techniques are driven by the problems such as long lead time, high WIP, bottleneck, unbalanced lines, etc. One of the possible ways to facilitate this is by applying a classification method.

2.3.2 The need for a classification scheme

A number of techniques are available to discover various patterns in a data set (Bose and Mahapatra, 2001). These include: i) rule induction (RI) which provides a decision tree or a set of decision rules; ii) neural network (NN) which comprises of a set of input nodes and output nodes through a set of hidden nodes, thus forming a multi layered network; iii) case-based reasoning (CBR) which stores examples of problems in a case-base including the problem description and its solution then uses them in the machine learning task; iv) genetic algorithms (GAs) which are a family of search procedures based on the theory of natural selection and evolution; v) inductive logic programming (ILP) uses first order predicate logic to define a concept by using a set of positive and negative examples before classifying new examples; vi) cladistics through phylogenetic tree which represents the evolutionary relationships among a set of entities or groups of organisms.

Cladistics was initially developed by linguists to understand the evolution of language and later was popularised in the field of evolutionary biology. In this field, cladistics helps to analyse the evolutionary relationships between groups of organisms to construct their taxonomy or family tree. The principle behind it is that organisms should be classified according to their evolutionary relationships, and the way to discover these relationships is to analyse what are called primitive (ancestor) and derived characters (descendant). Primitive characters are the attributes of a plant or animal which all members of the group possess, for example, having four legs is primitive for mammals because they inherited this characteristic from their common ancestor. Cladistics was used to analyse the diversity of the automotive assembly industry and to identify their characters which will not only enable grouping, but also help them clearly identify the characteristics which are appropriate for their business needs (McCarthy et al., 1997). Cladistics has also been applied in other areas, for example electronics manufacturing (Fernandez and McCarthy, 2002) and hand tool manufacturing (Leseure, 2000). In the context of organisational change, cladistics has been applied in benchmarking (Fernandez et al., 2001), measuring agility (Tsinopoulos and McCarthy, 2000) and change management (Rakotobe-Joel et al., 2002).

The novelty of the proposed research pushes the boundary of current and related research in the area of rapid simulation model development. The proposed research will provide a substantial advancement of knowledge from previous work by:

- Exploring the use of cladistics and evolutionary analysis as a basis of the classification of both manufacturing systems and the problems being addressed using simulation.
- Investigating a new way of rapidly generating simulation model templates based on both typical manufacturing systems to be modelled and the problems to be addressed.
- Shifting the concept of ‘model building’ towards ‘model assembling’, where model elements can be retrieved from a ready-to-use component library and the complete model will be generated automatically in order to speed up the model development.

2.4 Chapter summary

The aim of this research is to investigate a new method to rapidly build a simulation model which is capable of facilitating the model building process and reducing the learning curve of simulation studies. A few options are available to realise this idea, one of which is by developing a new simulation package or tool which is capable of building a model in a short time. However, this option was not taken into account for various reasons: i) limitation of time; ii) time-consuming; ii) no expertise and no depth of experience or knowledge in developing simulation software or packages; iv) this option is not the aim of this research.

Instead, this research focuses on investigating a new method to rapidly build a simulation model based on the classification of problems and a template approach. Problems in manufacturing systems have been chosen as the key subject for this research. In addition, there must be a reason and need for the usage of simulation and model building. Most of these needs are driven by problems such as high operating cost, long lead time, high WIP, unbalanced lines, etc. In the other words, simulation is used to tackle or monitor problems being faced in manufacturing activities. This research therefore focuses on investigating a new method to rapidly build a simulation model based on similarity of problems to be tackled and similarity of the decision path to be made. As a result, a prototype will be developed to demonstrate the proof-of-concept regarding the new method which is capable of rapidly building a simulation model based on classification of problems using cladistics technique and template approach. This concept can be implemented in any software or simulation tools and the final deliverables may not be using Witness software. Since problems are evolved over time and continuously developed, the cladistics technique is used to classify all the problems.

The sample data of problems were gathered from the literature review mostly from journals and conference papers. Even though the sample data of problems came from the literature review, they are more than enough to represent common problems established in assembly lines. These problems are classified using cladistics in the form of a tree which is called a cladogram. Based on the established classification, suitable elements required for model building and performance measures are generated as templates.

It is imperative to develop and provide a solution that can both speed up model building and make it easier. User-friendly prototype development which integrates: i) the common problems in manufacturing systems; ii) evolutionary analysis and classification of the problems using cladistics; iii) physical and performance measurement elements developed using the template approach, can be one of the solutions to reduce the model development time. Additionally, the time spent on the learning curve in creating a model among non-expert users with little simulation experience can be reduced.

3 RESEARCH PROGRAMME

This chapter presents the aim and objectives established for this research. In addition, the research methodology with the associated objectives to be achieved and the expected deliverables, is briefly presented.

3.1 Research aim and objectives

The aim of this research is to investigate a new method to facilitate model building in order to reduce the model development time using the template approach and cladistics technique. The new method, it is believed, will help users in model building so as to minimise model development time. Therefore, a set of objectives has been established in order to achieve the aim:

- To establish an understanding of typical problems in manufacturing systems (especially assembly lines).
- To apply a cladistics technique to problems (sample data) established for classification and evolutionary analysis.
- To develop a prototype which can rapidly build a simulation model using a template (reusable elements) approach based on established classification.

3.2 Research methodology

The three objectives above lead to four stages in the research programme which represents the methodology used for the research. The first stage defines the typical problems in manufacturing systems, especially in assembly lines. The purpose of this stage is to establish and develop an understanding of the problems and their evolution. The second stage then uses the sample data gathered from the first stage, grouping and classifying the information in the form of a cladogram. The third stage focuses on the development of the prototype, based on the established cladogram. Finally, testing and validation are carried out in the fourth stage.

The four stages of the research programme will be described in the following sub-sections as shown in Figure 3-1.

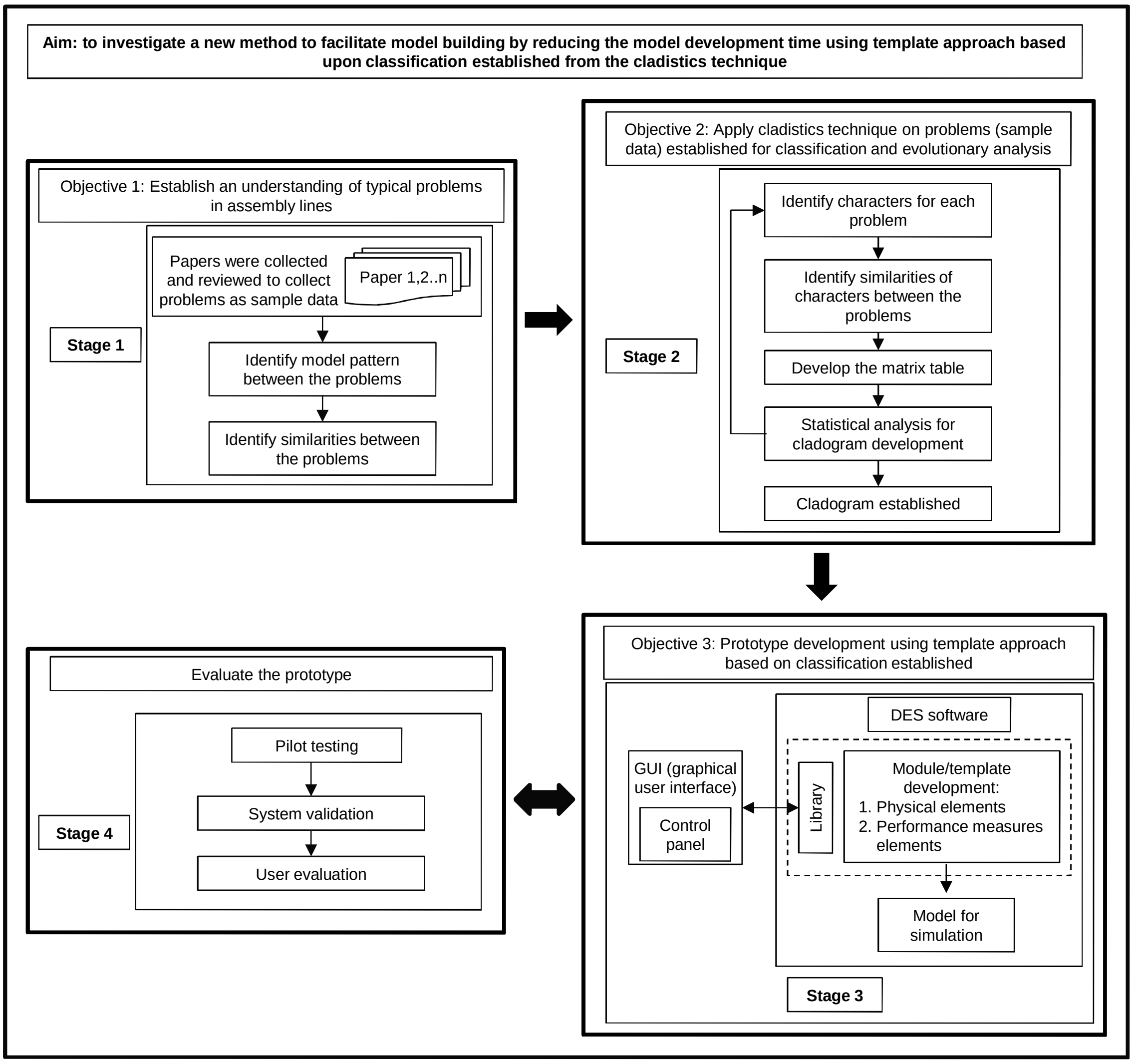

Figure 3-1 Research methodology

3.2.1 Stage 1: Collection of typical problems in assembly lines

In this stage, some sample data of problems are needed for classification purposes. In order to collect and develop an understanding of typical problems in assembly lines, an extensive literature review from journal publications and conference proceedings was carried out. The problems collected from the literature review had taken a few factors into account, such as the definition of search strategy, by identifying the relevant data sources, time frame and keywords used based on a broad range of publication databases. The search strategy was mainly focused on the problems in assembly lines.

Before selecting the relevant papers for review, the list of papers which appeared based on the keyword combinations were filtered by removing any duplicate records. Next the titles were scrutinised in order to increase the number of hits of relevant publications. Finally, the abstracts and contents of all papers were reviewed before selecting papers for a full review. This stage and the key findings established will be discussed in more detail in Chapter 4.

3.2.2 Stage 2: Cladistics and classification

An evolutionary analysis technique which is called cladistics has been used in this research. The purpose of this technique is to classify the sample data collected in Stage 1 and to demonstrate the evolution of each problem in the form of a tree structure which is called a cladogram. The cladistics technique has been chosen for this research for the following reasons:

- It has been recognised as one of the techniques for the evolutionary analysis

- Since problems in assembly lines evolve over time and are continuously developed, cladistics has been chosen as the most suitable technique to classify the problems.

The cladogram is developed using MacClade software (Maddison and Maddison, 2005) which is one of the tools available for evolutionary analysis, scientifically named phylogenetic analysis. MacClade is a MacOSX based version which can be used as data editor, tree viewer and analytical tool for use with other programs for parsimony analysis (searching for the shortest tree). The cladogram is developed based on the matrix table which consists of two main parts: i) Taxa (subjects are being studied); ii) Characteristics for each taxa. In the context of this research, taxa are represented by the problems and characteristics are represented by the causes for each problem. Therefore the problems and their characteristics were identified and extracted based on the sample data collected in Stage 1 in order to develop the matrix table. Then the MacClade software can do all the statistical analyses based on the matrix table developed, grouping the taxa and generating the cladogram. The details for this chapter will be extensively presented in Chapter 5.

3.2.3 Stage 3: Development of the prototype

The prototype has a graphical user interface (GUI) or control panel which is linked to the discrete-event simulation (DES) software called Witness (Lanner Group, 2005). The control panel is developed using Visual Basic software and is capable of providing some of the physical and performance measure elements for simulation modelling in Witness. Based on the cladogram established in Stage 2, some of the important elements required in model building and simulation were identified. These elements will be created as modules or templates and all of them kept in a library. All the templates will be continuously developed based on the cladogram established.

Since the problems evolve over time, the cladogram will be continuously updated. When a cladogram is updated, the library of simulation templates will also be updated. The library is a repository for all templates that can be changed, added or deleted over time depending on changes in the cladogram.

The control panel is used to interact with the DES software. This control panel will help the user to build the model, and provide the physical and performance measure elements in real time. Furthermore, the control panel will provide a step-by-step instruction, guiding the user in building the model and choosing the suitable elements for the performance measures. The details for this will be extensively presented in Chapter 6.

3.2.4 Stage 4: Testing and validation of the prototype

The purpose of this stage is to validate the prototype developed and to investigate that the aim and objectives established have been achieved. It must be borne in mind that model validations in any simulation study do not intend to prove that a valid model is one that behaves like the real system. In addition, the validation process depends upon a particular goal and established assumptions. This stage starts with the initial feedbacks gathered from the pilot testing. The final refinements of the prototype were carried out based on the initial feedbacks established before the final validation process. Details of the refinements will be discussed thoroughly in Chapter 7. Next, validation and confirmation studies were carried out through feedback forms and exercises provided. A group of users was asked to perform some exercises in two modes: i) do the exercises manually using the simulation tool provided; ii) do the same exercises using the prototype developed. Time was recorded for each exercise. Feedback forms were provided to capture users' perceptions of ease-of-use, friendliness and usefulness of the prototype. The results established can be used as an indicator to measure to what extent the prototype developed can help users in model building. The overall results and feedback will be discussed in more detail in Chapter 7.

3.3 Chapter summary

This chapter addresses the aim and associated objectives to be achieved for this research. The research methodology proposed comprises four stages: i) collection of typical problems in assembly lines; ii) cladistics technique and classification; iii) prototype development; iv) testing and validation of prototype. The research methodology starts by collecting and developing a thorough understanding of the various types of problems in assembly lines. Previous research and literature from various sources, predominantly from journals and conference proceedings in the area of simulation and modelling were reviewed. The principal deliverables are a distribution of problems in assembly lines and relationships established between those problems, showing not only the nature of typical problems but also the characteristics for each of them. Both will be used as a sample of data for the classification development in the next stage. In the second stage, a tree structure diagram called a cladogram will be developed using a cladistics technique that can be used to represent the history of evolution of a group of problems in assembly lines. In the third stage, a prototype of a rapid model generator will be developed in order to evaluate the effectiveness of the proposed evolutionary analysis based on the established cladogram. In this stage, the problems and their characteristics will be converted into a model library, from which collections of model elements in the form of templates will be retrieved and customised further to suit the needs of the modellers. In the fourth stage, validation and testing will be carried out using the *walk-through* (expert judgement) method, where users are required to perform some exercises using the prototype developed. The purpose of the validation process is to identify to what extent the prototype can help users in model building. The confirmatory study will be carried out through the feedback forms provided in order to capture users' perceptions of ease-of-use, user friendliness and usefulness of the prototype developed.

4 COLLECTION OF TYPICAL PROBLEMS IN ASSEMBLY LINES

The purpose of this chapter is not only to establish a thorough understanding of typical problems and their evolution in a manufacturing system but to collect a sample of data, i.e. the problems extracted from the literature review, as shown in Figure 3-1 (Stage 1). The sample data (problems) are required for classification development, then the classification established will be used to generate the templates. Since the scope of the manufacturing system is too large, this research focuses only on assembly lines. As the problems are evolved over time and continuously developed, a cladistics technique is used to classify all the problems. The sample data of problems were gathered from the literature review mostly from journals and conference papers. Even though the sample data of problems have come from the literature review, they are more than enough to represent common problems established in assembly lines. Looking at the overall picture of the review, the specific problems that simulation is used to deal with can be represented in the form of classification. These problems are classified using a cladistics technique in the form of a tree which is called a cladogram. Based on the established classification, suitable elements required for model building and performance measures are generated as templates. In terms of research questions, this research addresses a few questions as given below:

- What are the typical problems in manufacturing systems, especially in assembly lines?
- What is the relationship between one problem and another? Is there any evolution?
- What are the common elements used in simulation to monitor those problems?

The purpose of these questions is to guide the search strategy in order to develop a better understanding of the research.

This chapter is composed as follows: Section 4.1 addresses why problems have been chosen as the key factor for this research. Section 4.2 illustrates a search strategy used for collecting the problems. Section 4.3 shows the established results. Key findings from the reviewed papers are presented in Section 4.4. Finally, Section 4.5 provides a summary of this chapter.

4.1 Why problems?

"*Every simulation study begins with a statement of the problem.*" (Banks, 2000)

This chapter begins with one statement narrated by Jerry Banks in his publication entitled "Introduction to Simulation". It shows that there must be a reason and a need for every simulation study. Simulation is used to help users with problem solving (Shannon, 1992). That is why problem formulation became one of the criteria that needs to be taken into account in simulation studies (McLean, 2003). It is believed that most of the reasons and needs for simulation study are driven by problems. It is therefore problems in manufacturing systems, especially in assembly lines, that have been chosen for classification development using a cladistics technique and prototype development purposes.

4.2 Search strategy

The search strategy performed consists of a few factors such as identifying the relevant data sources, time frame and keywords. This strategy covers a broad range of databases selection including journals and conference papers. These included Compendex, Inspec, and Emerald. These databases permit access to a wide variety of publications such as International Journal of Production Research, European Journal of Operational Research, International Journal of Advanced Manufacturing Technology, International Journal of Flexible Manufacturing System, Winter Simulation Conference Proceedings, Production Planning and Control, Computers and Industrial Engineering, International Journal of Production Economics, and Journal of Intelligent Manufacturing.

General keywords such as manufacturing systems, manufacturing and simulation, manufacturing problems, manufacturing simulation and modelling manufacturing disturbances, and manufacturing issues provide thousands of hits but only a handful of useful papers. Therefore an effective search strategy has been performed in order to improve the collection of papers.

The search strategy has been narrowed down by using a broad range of keyword combinations. These include common phrases or controlled vocabulary in the manufacturing environment such as manufacturing system, manufacturing, assembly line and production system. On top of this, specific keywords for problems have been used in order to narrow down the focus of the papers selection, such as number of machines, machines layout, line layout, conveyor, transporter, material handling, buffer size, buffer location, product mixed, batch, labour, throughput, bottleneck, work-in-progress (WIP), lead time, productivity, machine breakdown, number of products, imbalance of cycle time, reject/rework, scrap, blockage, starvation, setup time, waiting time, asynchronous, synchronous, single model, mixed model, multiple model, assignment of task/operation, duplication of stations, operation cost, production scheduling, line balance, paced line, unpaced line, parallel lines, reconfiguration, and material flow. Several strings featuring different combinations of these keywords were used in this study. In addition, the time frame for this study was chosen initially to include only literature published between 1960 and 2009. Other criteria that have been taken into account in this study are retrieving results from any of the following fields: subject/title/abstract; document type must be in journal or conference paper; and the language must be in English. Subject categories and controlled vocabulary have been chosen in order to describe the content of a document in the most specific and consistent way possible.

Before selecting papers for a full review, papers which appeared from the list of hits for each keyword combination were filtered by removing any duplicate records, then the titles were examined for relevance to the study. Lastly, the abstracts and contents of all papers were reviewed before selecting papers for a full review. The initial results show that thousands of hits had been achieved based on the combination of keywords used in the search and it was not therefore practical to review the extensive list of literature.

4.3 Results

The search strategy has guided the author to the identification of relevant data sources. Most of the key words are combined with the terms "manufacturing system" and "production system" as the subject categories in order to limit the search to the related area. Besides that, each keyword has been combined with common vocabulary as a specific way to retrieve the relevant papers. After looking at the hits, many of the publications that were retrieved came from the search string of specific keywords as mentioned above.

Following the review of publications that were retrieved based on the filtering process that was carried out, 196 papers from various international journals and conferences were selected as part of this research. Each paper has been carefully reviewed to identify the key findings or main themes which consist of main problems and associated characteristics. This allows for a clear understanding of the current research direction. Finally, the findings and issues have been summarised to form the research aim, objectives and programmes. On the basis of this analysis, the following key findings were developed and are presented in Section 4.4.

4.4 Key findings and analysis

4.4.1 Distribution of problems

The distribution of problems from the reviewed papers shows that the most common problem that has been reported in the reviewed papers is related to ALB (assembly line balancing) with a percentage of 68% as shown in Figure 4-1. There are a few factors that have been considered as the root causes for the lines not being balanced, such as assignment or distribution of operations/tasks among the stations in the production lines, product model, reconfiguration of resources, workpiece and movement, parallelisation, etc.

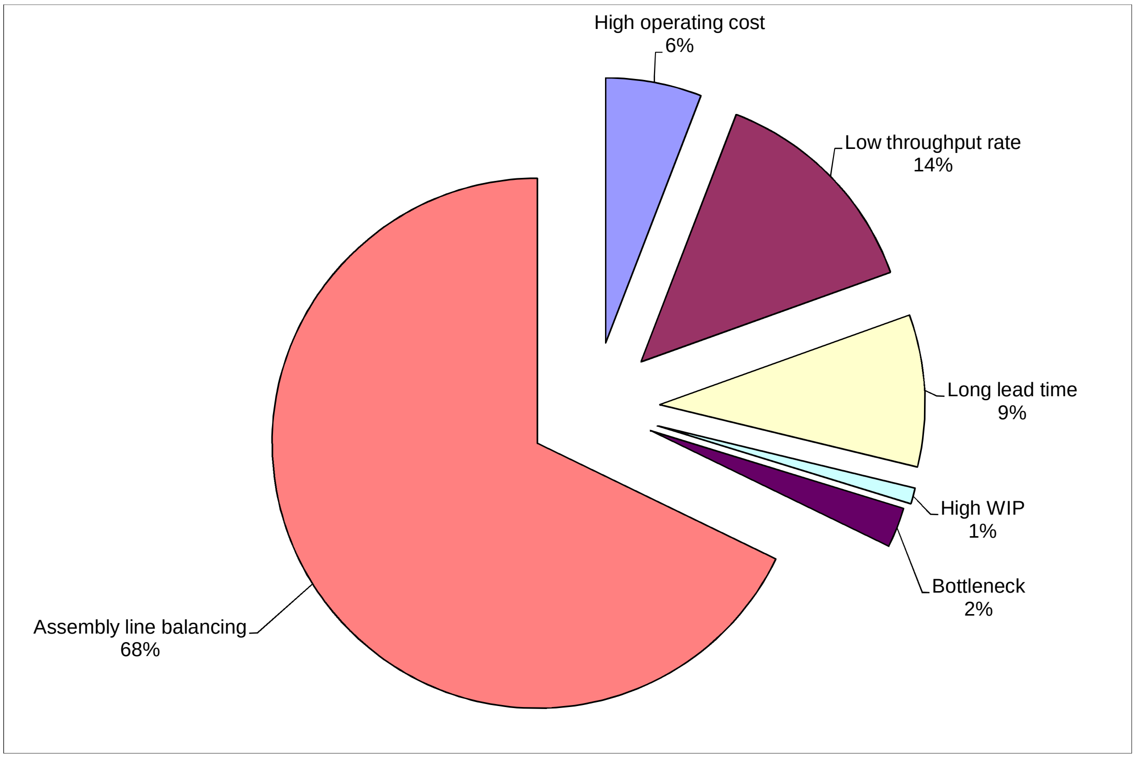

Figure 4-1 Distribution of problems

Based on the distribution established, 6% of the collected problems are related to high operating cost. Malakooti (1994) also reports that imbalance of the entire production system may increase the total operation cost. This has happened due to improper number of stations, and problems related to buffer allocation which consists of buffer size and buffer location. These two factors have a significant effect on balancing the cycle time among the stations in the system. Moreover, improper buffer size and location not only affect the space requirement in the layout planning but may also influence the installation cost which can have a direct impact on operation cost (Aksoy and Gupta, 2005; Anderson and Moodie, 1969; Jeong and Kim, 2000; Lee and Ho, 2002; Lee and Kim, 1997; Zequeira et al., 2004).

On the other hand, 14% of the reviewed papers deal with the problem of low throughput rate. Generally, throughput rate is influenced by WIP and lead time.

The significant impacts of low throughput rate are high WIP and long lead time. Based on the reviewed papers, throughput rate can be maximised by looking at the buffer allocation (size and location) in the production system. Improper buffer size and location may increase the operational cost and reduce productivity. This approach is very meaningful in the case of material (workpiece) flow disruption due to unreliable line or machine failure. Therefore the production is still running without totally relying on upstream and downstream stations. In such circumstances the performance measure of throughput rate can be used to monitor the average number of completed product per time period (Chow, 1987; Enginarlar et al., 2002; Gershwin and Schor, 2000; Hillier and So, 1993; Huang et al., 2002; Papadopoulos and Vidalis, 2001; 1998; Pourbabai, 1989; Powell, 1994; Powell and Pyke, 1998; Shi and Men, 2003; Spinellis and Papadopoulos, 2000; Tempelmeier, 2003; Vidalis et al., 2005; Vouros and Papadopoulos, 1998).

Apart from considering buffer size and location, WIP also needs to be considered in maximising throughput because high WIP has a direct impact on throughput rate. Too many buffers will increase the WIP in the system and as such may lead to long lead times (Chakravorty and Atwater, 2006; Conway et al., 1988; Hemachandra and Eedupuganti, 2003; Huang et al., 2002; Koo et al., 2007; Lutz et al., 1998; Nakata et al., 1999; Sivasubramanian et al., 2003; Szendrovits et al., 1990). Other factors that need to be considered in maximising throughput rate is eliminating bottlenecks through proper balancing of cycle time and workload among stations (Byrne and Jackson, 1994; Kuroda et al., 1999; Potts and Whitehead, 2001). Konopka (1995) also reports that low throughput rate problems can also be solved by reducing parts rejects or reworks through allocating buffers with the proper size at the correct location, especially at the bottleneck station which has the longest operation/task time.

Based on the literature, 9% of reported problems are related to long lead time. Several authors (Burgess et al., 1993; Flynn, 1987; Garza and Smunt, 1991; Ko and Egbelu, 2004; Morris and Tersine, 1990; Wemmerlov, 1992) have reported that long setup time is one of the factors that has a significant impact on long lead time. Apart from that, long lead times also occur due to improper allocation of batch size (Ang and Willey, 1984; Ekren and Ornek, 2008; Jacobs and Bragg, 1988; Karmarkar, 1987; Kuik and Tielemans, 2004; Kum and Jacobs, 1992; Shafer and Charnes, 1993; Suresh, 1992; 1991). Small batch sizes require high numbers of setups but small batches are easy for operations/tasks allocation, line balancing, distribution of work content or station load, and scheduling due to increases in demand.

The reviewed papers also described that bottleneck problems occur due to imbalanced cycle time between stations – formerly known as assembly line balancing problem (Tjahjono and Fernández, 2008). The assembly line is balanced when the tasks or operations are properly distributed among the stations in the system. Therefore, the station times or total task times for each station are in feasible range of cycle time. In addition, bottleneck problems can be eliminated by taking into account the factor of machine breakdown (Ju et al., 2007; Qi et al., 2008; Sengupta et al., 2008). In addition, bottleneck problems can be solved effectively by reducing blockages on upstream stations and starvations on downstream stations (Li et al., 2009).

4.4.1.1 Distribution of problems in assembly line balancing

Assembly line balancing problems can be extended to several other problems such as product model, reconfiguration in resources, workpiece and movement, parallelisation, and task assignment problems, as shown in Figure 4-2. It can be clearly seen that the most common problem that has been reported in the reviewed papers is related to product model, with 34%. Product model consists of single model, mixed model, and multi/batch model. These three factors can have a significant impact on assembly line balancing. The second highest percentage is workpiece and movement (21%) and this is followed by task and assignment problem at 18%. The fourth most common problem is parallelisation, which garnered a percentage of 14% from the overall proportion. At the other end of the scale, reconfiguration is the least common problem that has been reviewed from the literature. The next subsection will discuss each of these in detail.

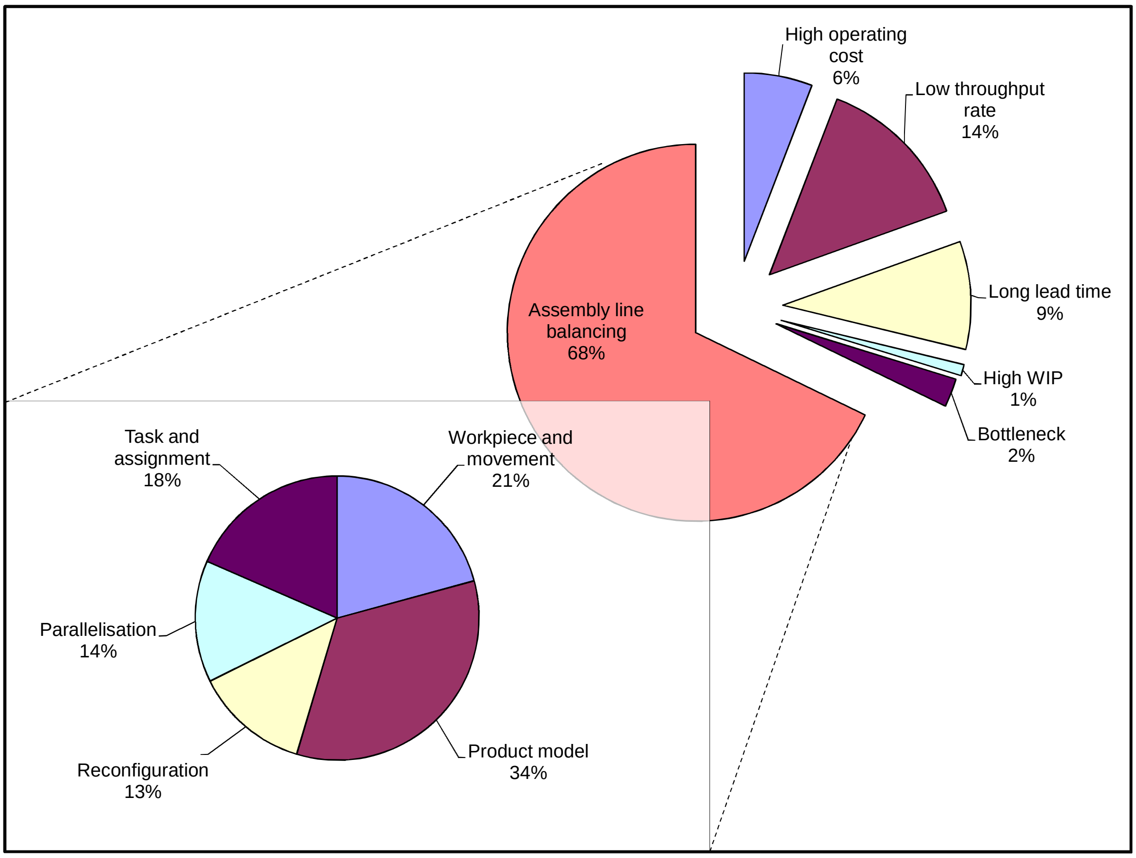

Figure 4-2 Distribution of problems in assembly line balancing

4.4.2 Establishing relationship between problems in assembly line balancing

The literature review shows that one of the causes of high total operation cost in production systems is the assembly line balancing problem. This happens due to several related problems, such as low throughput rate, long lead time, high WIP and bottleneck problems. Based on the reviewed papers, operating cost is increased due to low throughput rate problems, long lead times and high WIP. In order to solve these problems, one item that needs to be looked at is the bottleneck in operations. At this level, assembly line balancing can be considered as one of the possible factors that lead to bottleneck problems. Indirectly, this kind of relationship provides some sort of evolution among the related problems, as shown in Figure 4-3 and Figure 4-4. This information can be used as a guideline to produce the possible solutions for every level of evolution.

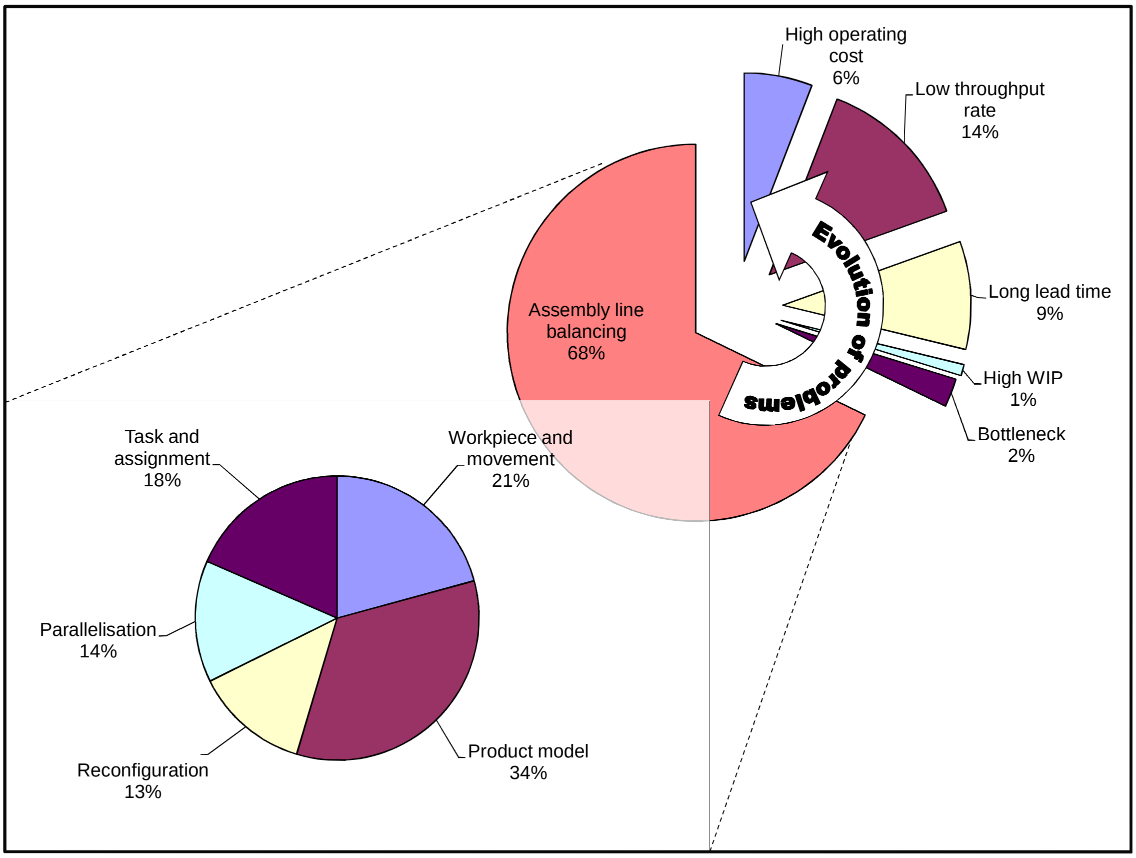

Figure 4-3 Relationship between other problems and assembly line balancing problem

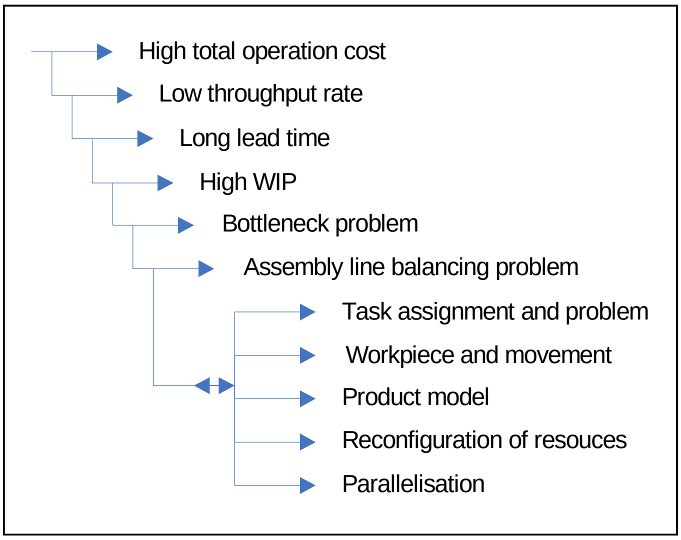

Figure 4-4 Top down illustration of other problems and assembly line balancing problem

4.4.2.1 Workpiece and movement

The movement of workpieces in the assembly line production can be classified as paced line and unpaced line as shown in Figure 4-5. In the paced line, all stations start their operations/tasks at the same time and then workpieces are sent to the next station at the same rate (Boysen et al., 2007). In this type of movement, the given cycle time is fixed which restricts the station times (process times) at all stations. The line is balanced as long as the station time does not exceed the cycle time given to that station. In the case of station times being too short, such circumstances lead to a high number of stations' idle times. This occurs when the stations need to spend a lot of time waiting for the next arrival of a workpiece after completing its operations. Another factor that needs to be considered in the paced line is the continuous transportation movement of workpieces, such as the conveyor. The balancing of the line is influenced by length between stations and movement rate of the line. If the movement of the workpieces is too fast and not synchronous with the value of the given cycle time, the operations/tasks could not be completed in time. Eventually, this may increase the operational cost for the whole production (Carter and Silverman, 1984; Gökçen and Faruk Baykoç, 1999; Henig, 1986; Lyu, 1997; Kottas and Hon-Shiang Lau, 1981; Lau and Shtub, 1987; Sarin and Erel, 1990; Sarin et al., 1999; Shtub, 1984; Silverman and Carter, 1986).

Unpaced line production consists of an asynchronous line and a synchronous line. In the unpaced asynchronous line, the workpieces are transferred after the station has completed all their required operations/tasks. In other words, the workpieces are transferred individually as soon as the operations/tasks are completed (Boysen et al., 2007; 2008). In the case of an unreliable line, machine breakdown problems will have a significant impact on the production line. This machine breakdown problem leads to blockages and starvation problems among stations. The nearest upstream station will be blocked because the workpiece cannot be transferred to the next station. Meanwhile, the downstream station will be starved or idle because it cannot receive the workpiece. This leads to high waiting times of workpieces among the downstream stations and total stations' idle times will increase. At this point, the current problem continually evolves to create a few more problems such as long lead time and high WIP. In the end, the throughput rate of the production system is low and customer demands might not be achievable. In order to solve this problem effectively, it is worth allocating the buffers in the production system. This factor might lead to decision problems regarding buffer size and location. Last but not least, the installation cost of buffers needs to be taken into account because it might have a significant impact on the throughput rate of the production system (Baker et al., 1990; Buzacott, 1968; Dolgui et al., 2002; Hillier and So, 1991; Hillier et al., 1993; Malakooti, 1994; Powell, 1994; Suhail, 1983).

In an unpaced synchronous line, all stations transfer their workpiece simultaneously. Cycle time is determined by the station with the longest station times. The workpieces are transferred at the same point in time but all stations in the system need to wait until the slowest station finishes its operations/tasks, therefore, the allocation of buffers is negligible.

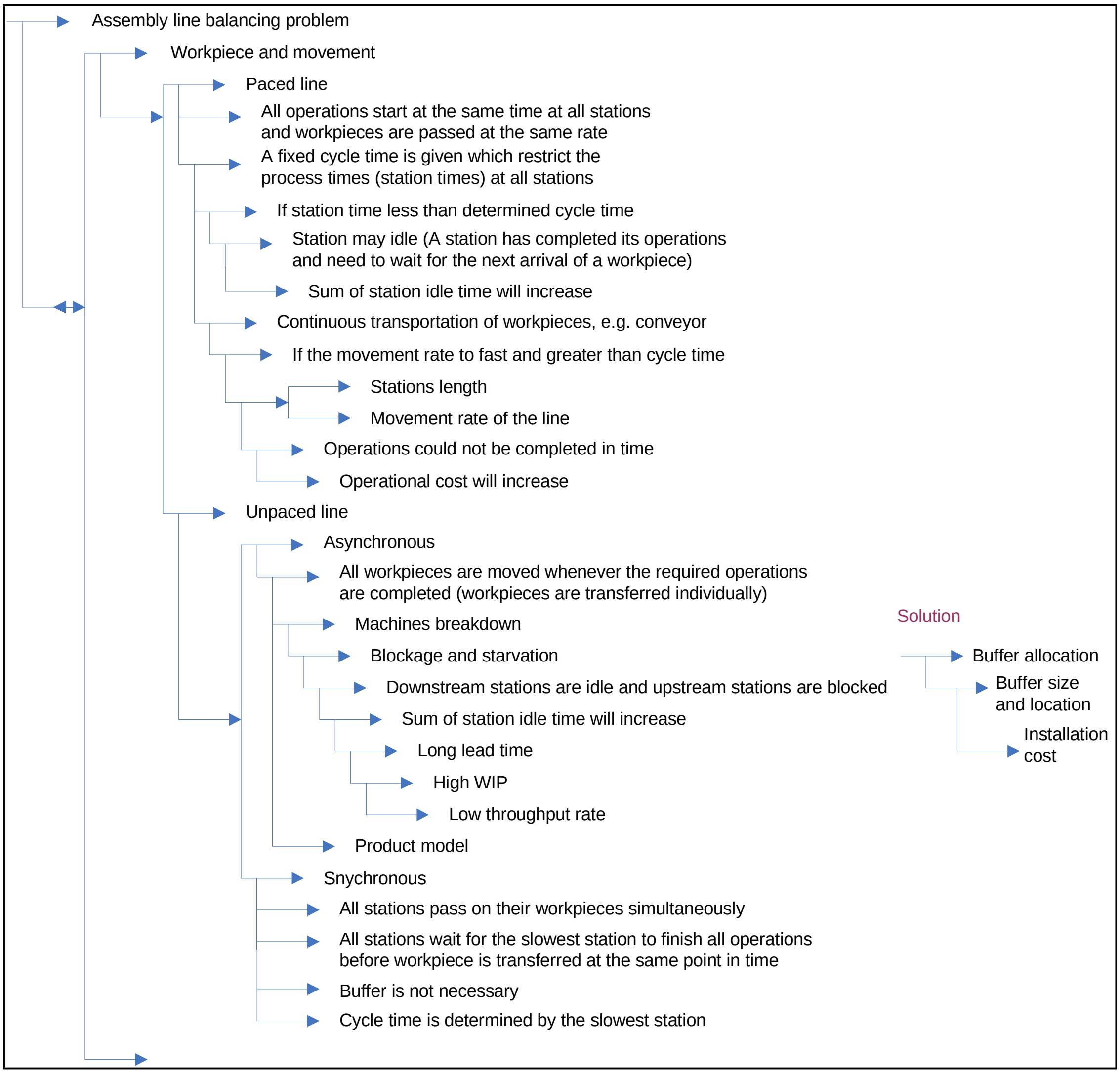

Figure 4-5 Movement of the workpiece and related problems

4.4.2.2 Product model

Product model in this subsection addresses three factors that commonly affect the assembly line balancing problem such as single model, mixed model, and multi/batch model, as shown in Figure 4-6.

Traditionally, assembly lines with high volume production of a single product are known as single model production (Becker and Scholl, 2006; Boysen et al., 2007; 2008). Commonly, this type of production line does not require more than one set-up because there is no variation of products and therefore there is no variation in operating times for this kind of production.

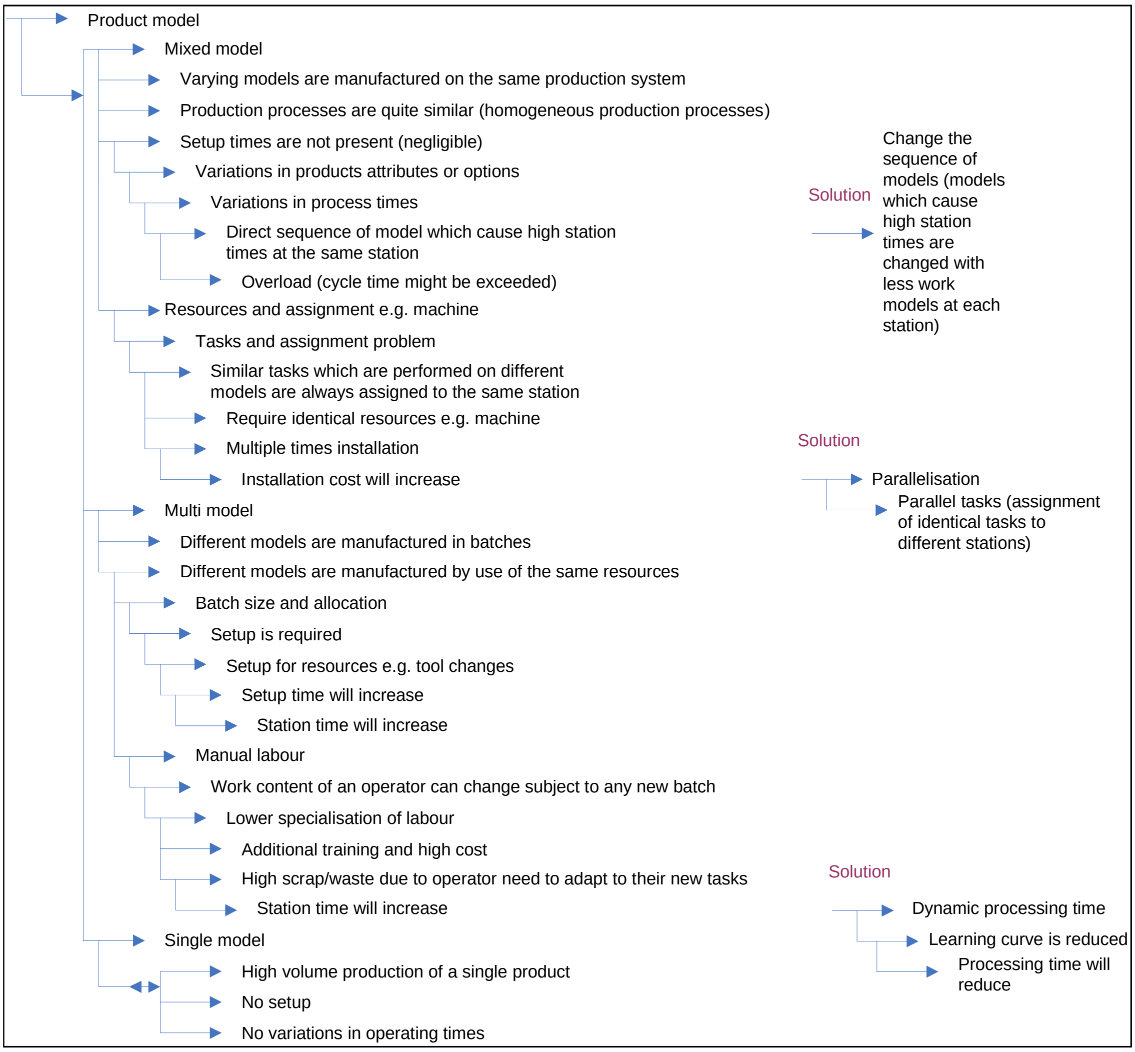

Figure 4-6 Product model and related problems

A mixed model production line consists of different models or products which are manufactured in the same production system (Boysen et al., 2008). Production operations/tasks are quite similar between the stations because all models are based on the same product and the difference is only in terms of specific features (attributes). As a consequence, setup times can be assumed as not present or negligible. The variation of product attributes leads to variations in processing times. Therefore, the direct sequence of models which cause high station times at the same station needs to be considered very carefully because it may lead to overload problems. In the case of overload problems, the planned cycle time will be exceeded. As a solution, the current sequence of models which cause high station times need to be changed by allocating fewer operations/tasks models. Apart from that, another problem that needs to be considered in balancing the mixed model production line is the integration of assignment of resources and tasks. Whenever operations/tasks have been decided, equipment selection and design problem will be given priority in balancing the assembly line. Thomopoulos (1967) reports that similar operations/tasks which are performed on different models are always assigned to the same station. This may require installation of identical resources such as duplication of machines. Consequently, multiple times installation may increase the operational cost. One of the available solutions for this problem is the implementation of parallel tasks in the line which require the assignment of identical tasks to different stations.

The main feature in this multi/batch model production is that assembling processes are performed on different models in batches. Batches of models are manufactured using the same resources such as stations or machines (Boysen et al., 2007). In this type of workpiece movement, batch sizes play an even greater role and this factor needs to be taken into account very carefully. In addition, setup for resources such as tool changes or machinery reconfiguration needs to be done due to the different batches of models and this in turn may lead to high setup times. As a result, the process times or station times will increase gradually which directly affects the lead time. Another possible constraint or problem that can evolve from this multi/batch model is related to manual labour. Work content or station load of an operator on the stations could be changed, with the introduction of any new batch of models. Too many changes will reduce the level of specialisation among labourers and therefore will require additional training which might increase the cost. Other than this, high scrap/waste problems will take place due to labourers' needing to adapt to their new operations/tasks. As a consequence, the total processing times at the stations will increase steadily at these times but may reduce slowly once the labourers get used to those new operations/tasks. These kinds of processing times could be referred to as dynamic processing times because they are based on the learning curve of labourers at a particular period of time.

4.4.2.3 Reconfiguration of resources

Instead of first time installation of resources, assembly line balancing problems are also evolved from the reconfiguration of resources in the production system (Falkenauer, 2005). Reconfiguration refers to the rearrangement of resources to the new structure of the production lines (Boysen et al., 2008). This new arrangement of resources will affect the distribution of work content or station load among the stations, allocation of heavy equipment, especially heavy machinery, and reallocation of manual labour as shown in Figure 4-7.

The distribution of work content is influenced by several factors such as number of stations in the system and cycle time. There are two common objectives that need to be achieved in balancing the assembly lines: minimise the number of stations for a given cycle and minimise the cycle time for a given number of stations (Becker and Scholl, 2006; Boysen et al., 2007). It can be clearly seen that cycle time and number of stations are very important in reconfiguration subject to balancing the lines. In terms of heavy machinery and re-allocation, there are two possible constraints involved: position changed or unchanged. If the position of the heavy machinery is changed, consideration in terms of cost and space needs to be given. The changes may affect the movement cost and limitation of space available. If the position of heavy machinery is unchanged, task assignment problems need to be taken into account. Whenever the position of the heavy machinery cannot be moved, certain tasks which require those resources must be assigned to them. In other words, the tasks are fixed to that particular station and such conditions need to be given priority in order to balance the lines.

Apart from cycle time, number of stations, and tasks assignment problems, the sequence of operations/tasks needs to be addressed as one of the factors in balancing the lines subject to reconfiguration because any changes involved may directly affect the available sequence and a re-sequence might be required to smooth the production flow. One more possible constraint or problem that might evolve from the reconfiguration of resources is operator or manual labour reallocation. Work content or station load may change considerably based on the new reconfiguration and therefore allocation of labour might be needed. Too many changes in allocation of labour on stations leads to lower specialisation of labour, high training cost due to additional training being required and high scrap/waste of product. These constraints will increase the station times which affect the whole production system.

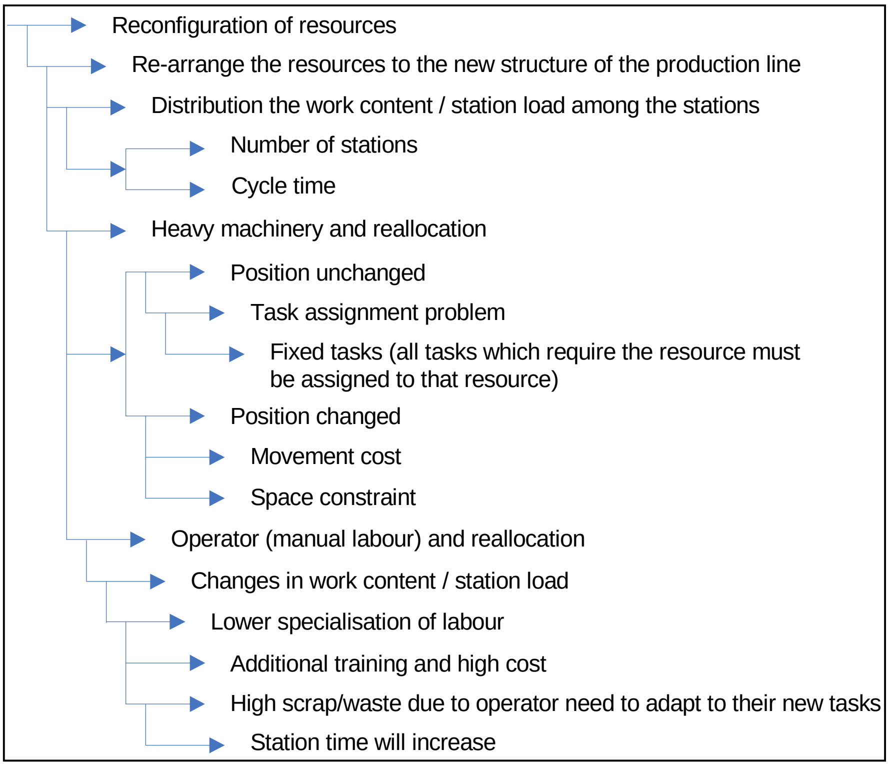

Figure 4-7 Reconfiguration of resources and related problems

Figure 4-7 shows how the reconfiguration of resources including distribution of work content or station load among the stations, allocation of heavy equipment especially heavy machinery, and reallocation of manual labour affects the line balancing.

4.4.2.4 Parallelisation

Parallelisation is one of the important factors that need to be considered in assembly line balancing. A few approaches have been proposed in order to balance an assembly line such as parallel lines, parallel stations, and parallel tasks, as shown in Figure 4-8.

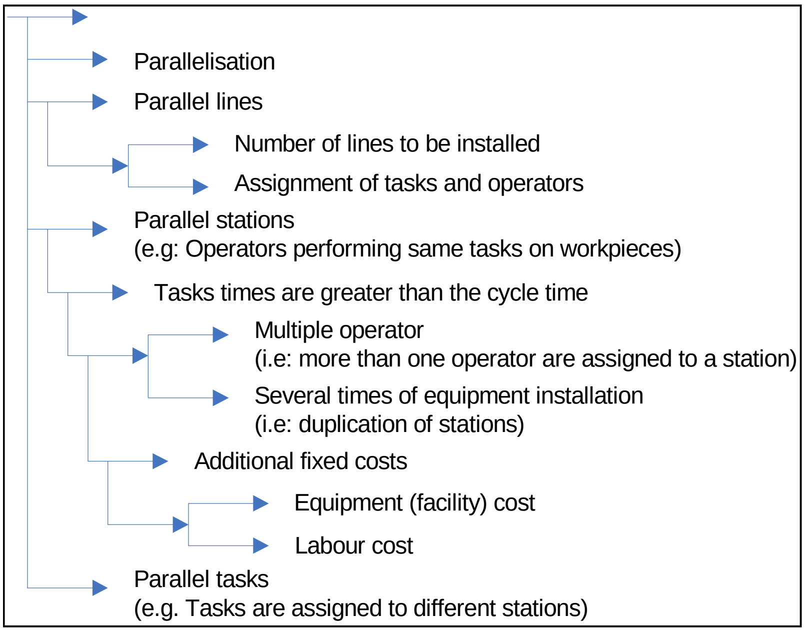

Figure 4-8 Parallelisation and related problems

The structure of parallel stations that has commonly been used in line balancing is duplication of stations. Duplication can be referred to as operators or stations performing the same tasks on the workpiece (Becker and Scholl, 2006). This approach is used whenever the total of tasks times is greater than the determined cycle time. Even though duplication of labourers or stations can be used to balance the line in terms of cycle time or minimising bottleneck operations, it requires additional fixed costs which consists of equipment cost and labour cost. Pinto et al. (1975) propose the concept of parallel tasks in balancing the lines. In this approach, same tasks (combination of several tasks) are assigned to different stations in order to balance the cycle time among the stations in the system. Another approach that can be used in parallelisation is parallel lines. There are a few constraints that need to be considered in parallel lines such as number of lines that need to be installed, assignment of operations/tasks to stations, and assignment of labour to operations/tasks or stations. All these constraints may have a significant impact on balancing the cycle times and operational cost.

4.4.2.5 Task and assignment problem

The assembly line is known as one of the important system in manufacturing activities. It is shaped based on operations/tasks to be performed. Initially, the entire tasks involved in a production system are broken down into smaller tasks. This may help the division of labour within the stations. These smaller tasks are then grouped into the specific station or labour. The integration between groups of tasks, stations, labourers and sequence of operations addresses an issue related to the task assignment problem, as shown in Figure 4-9. Many authors (Bartholdi, 1993; Bukchin and Masin, 2004; Bukchin et al., 1997; Kim et al., 2000) report that assignment of tasks to stations needs to take into account two possible characteristics: fixed tasks and type of station. Fixed tasks need to be considered in the case where heavy machines cannot be moved. Some tasks, therefore, need to be fixed at certain stations and cannot be assigned to others (Kilbridge and Wester, 1961). In contrast, type of station is one of the factors that need to be taken into account because some tasks are restricted to the type of station.

Incompatibility is also important in order to balance the cycle times because some tasks are not compatible with each other and therefore they cannot be assigned to the same station (Bautista and Pereira, 2007). Bautista and Pereira (2007) have also considered the sequence of operations/tasks in the same station and their effect on station time. The station time may increase due to additional time for setup in mixed or multi/batch production. Apart from the incompatibility of tasks, fixed tasks, and type of station, Bhattacharjee and Sahu (1988) and Lapierre and Ruiz (2004) have focused on the linking of tasks because some tasks are linked to each other and need to be assigned to the same station. The distance between tasks is also an important factor in the task and assignment problem. If the distance is too close, the workpiece that has been processed in the previous operation may not ready for the next operation.

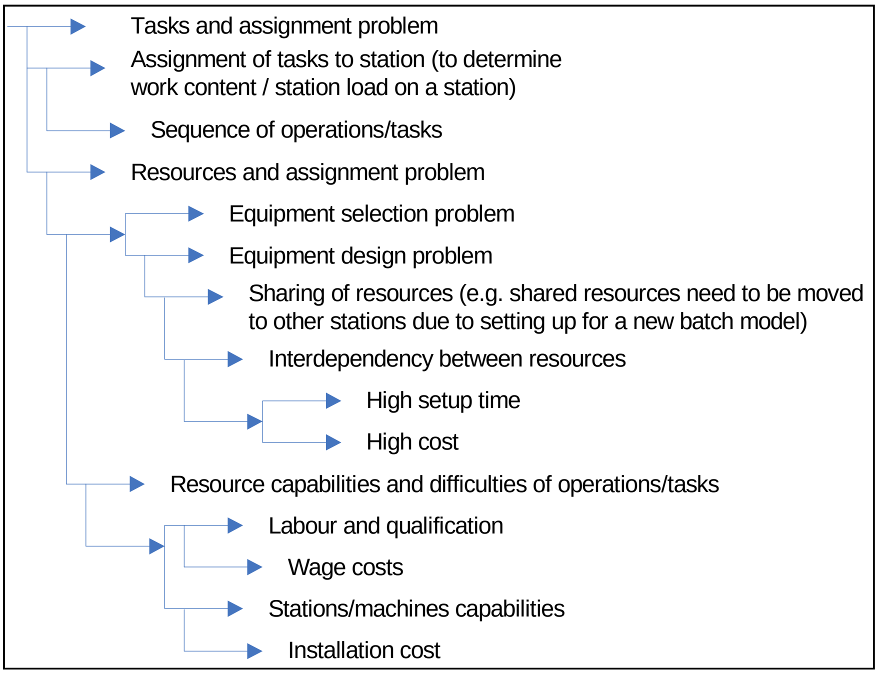

Figure 4-9 Task and assignment related problems

Tasks and assignment problem may lead to problems related to the assignment of resources. Assignment of resources is comprised of equipment selection problems and equipment design problems. One of the constraints that might be faced in equipment design problems is the sharing of resources. This factor may benefit in terms of reducing the investment cost but in the context of multi model production, shared resources might need to be transferred to other stations due to setting up for a new batch and this multiple-times installation may increase the cost. Apart from that, additional time may be required for the setup. Such types of interruption might end with infeasible line balances if not carefully considered.

On the other hand, resource capabilities and difficulties of operations/tasks can be factors that might evolve from the resources and assignment problem (Becker and Scholl, 2006). Some operations/tasks require a certain level of skill, experience and qualification of the operator. They might also require a certain level of capability in terms of the technologies and difficulties of the operations/tasks. Therefore, both factors will affect the whole operational cost of the production system including the wage costs for the operators and the installation costs for the stations.

4.5 Chapter summary

The main objective of this chapter is to establish a thorough understanding of the diversity and types of manufacturing problems, specifically in assembly line balancing. Based on the key findings, the evolution of the problems and other constraints involved can be traced effectively. This helps in developing the theoretical knowledge for this study. Apart from that, this information can be used to ease decision making in simulation modelling. As a result, this provides an effective and structured way to reduce the time in model building for simulation.

The principle deliverables of this chapter are a compilation of problems and characteristics in assembly lines and initial classification of problems. This compilation is very useful as a reference and foundation for a structured classification development of problems using a cladistics technique in the next chapter (Chapter 5). This information can be used to speed up model building based on the established cladogram. In addition, a thorough understanding of manufacturing systems especially regarding the assembly line balancing problem is fundamental knowledge that can be used to reduce the time for model building; meanwhile, it may improve the uptake of the simulation technique as a decision making tool. Chapter 6 then shows the development of the proof-of-concept prototype based on the key findings established in Chapter 5 which can help users to speed up model building and perform measures through simulation modelling in an effective way.

5 CLADISTICS AND CLASSIFICATION

In Chapter 4, a sample of data (problems) has been collected and extracted from the literature review. The sample data are very important for classification development. Based on this classification, specific elements required to measure or monitor problems established can be identified and grouped in the form of templates. The templates will help users or modellers in rapidly building a simulation model. Based on the key findings in Chapter 4, the preliminary classification established will generate the initial sequence of the evolution of the problems. Establishing a preliminary classification is very useful and will be fine-tuned in later sections. Since problems are evolved over time and continuously developed, cladistics has been chosen as a technique to classify all the problems. Therefore the final classification established in this chapter, using a cladistics technique, is not only grouping the problems into different hierarchies but is developed based on phylogenetic and evolutionary analyses as shown in detail in the next sections.

This chapter focuses on the fundamentals of cladistics, its theory and established classification that has been used in prototype development, as shown in Figure 3-1 (Stage 2). It is organised into several sections. Section 5.1 provides some initial introduction to classification. Section 5.2 concentrates on the introduction of cladistics. Section 5.3 focuses on the theory of evolution and shows the principles or fundamentals of cladistics. Section 5.4 presents interesting facts about evolution and the advantages of classification using a cladistics technique. Section 5.5 emphasises current research works or reviews of the cladistics technique in a non-biological environment. Section 5.6 discusses the characteristics and classifications established for this research. Section 5.7 provides a summary of this chapter.

5.1 Review of classification

The term classification can be divided into two: i) as a process to classify; ii) as an output of the process. The first definition refers to how the information is arranged or sorted. The second definition concerns the output generated from the process of arranging the information. The output can be in the form of framework, tree diagram, matrix table, etc. Based on these definitions, classification system and classification scheme have been used “to distinguish and identify classification as an output” (McCarthy, 2005).

Classification is one of the important approaches for arranging, organising, classifying and ordering groups of entities. The purposes of these activities are to develop an understanding about the entities, discover any advantages or drawbacks of relationships among the groups of entities and envisage future repercussions to assist decision making based on established classification. A classification can be defined as follows: “arranges materials in a way that tells us something about them: a mere list has no such character and a good classification provides a system which has high predictive value and will allow maximum information retrieval.” (McCarthy, 2005).

The formal classifications were initially produced by biologists and linguists. They coined a few terms with a diverse range of interpretations such as systematic, taxonomy, evolutionary, phonetic, cladistics etc. Systematics can be defined as “the study of different types of organisms, their distinction, classification and evolution”. Despite that, the term taxonomy is referred to as “a branch of systematics concerned with the theory and practice of producing classification systems and schemes.” (McCarthy, 2005).

In the biological environment there are three main approaches to classification: i) phenetics; ii) evolutionary; iii) cladistics. Phenetics is non evolutionary classification because it is developed purely based on physical appearance and behaviour of entities. Cladistics is based on phylogenetic analysis. Meanwhile evolutionary is the combination of phylogenetic and phenetic principles (McCarthy and Ridgway, 2000).

5.2 Introduction to cladistics

Cladistics is one of the techniques for classification and evolutionary analysis. It has been used widely within linguistics and the biological sciences. Cladistics is defined as "a method for systematically organising knowledge about a population of entities. It is a process for studying diversity and attempting to identify and understand laws and relationships that explain the evolution and existence of the variety of groups." (Tsinopoulos and McCarthy, 2000). Since cladistics is a technique born in the field of biology, it has been used to find the hierarchical links between objects on the basis of their similarity and available relationship between the objects (Rabino and Scarlatti, 2003). Table 5-1 summarises some other definitions of cladistics for greater understanding.

Table 5-1 Overview of cladistics in the context of evolutionary analysis and classification

Author	Overview of cladistics
Fernandez and McCarthy (2002)	"Cladistics is an evolutionary classification technique used within the biological sciences"
Leseure (2000)	"Cladistics was developed by linguists to understand the evolution of languages and it was later used and popularised in the field of biology. It helps in decision making and categorisation tasks. Moreover, it relies on precise concepts and terminology to discuss, test and revise systematically these decisions"
McCarthy and Tsinopoulos (2003)	"Cladistics is defined as a concept of using biological classification techniques which has two main principles such as phylogenetic (groups entities according to how they share common ancestors) and phenetic (differentiate purely on the physical appearance or behaviour of the configuration). From these principles emerge three approaches to classification such as evolutionary, cladistics and phonetic"
Tsinopoulos and McCarthy (2000)	"Cladistics is a method for systematically organising knowledge about a population of entities. It is a process for studying diversity and attempting to identify and understand laws and relationships that explain the evolution and existence of the variety of groups"
Fernandez et al. (2001)	"Cladistics involves the evolutionary relationships between entities with reference to the common ancestry of the group (a phylogenetic relationship) and the entities do not have to be biological if this method wants to be used in other areas, they simply have to demonstrate an evolutionary path using a cladogram. Cladogram provides

Author	Overview of cladistics
	a framework and information for better understanding between entities”
Stuessy and Konig (2008)	“The cladistic revolution (1965-1990) emphasized using characters and states of high phylogenetic content, determination of polarity (= directionality) of these states, use of shared derived character states (synapomorphies) for determining relationships, and employment of new algorithms for building trees (cladograms)”
AlGeddawy and ElMaraghy (2011)	“...are classified using a data clustering technique called ‘cladistics’ that generates classification trees called ‘cladograms’. The cladograms show the relationships between the studied taxa (singular: taxon), which is a group of studied entities. The objective of cladistics is to generate trees of minimum length (number of characters appearing on the tree)”
Buchanan and Collard (2008)	“Cladistics is the method of phylogenetic reconstruction that most biologists now rely on instead of phenetics”
Rose-Anderssen et al. (2009)	“The idea about this classification system is grouping species according to their recency of common ancestry. Therefore, “sister species” occurring during a recent evolutionary split will be classified together. This is done because it can be argued that they share a more recent ancestor than any of them with other species. Cladistic relationships are therefore fundamentally based on ancestral relationships”
Rose-Anderssen et al. (2011)	“Cladistics is based on random change which means that the specimens selected for study should have gone through the same change patterns. The specimens are then grouped into species. The characters responsible for a new type of system would inform the name of the system” “In cladistics, species are grouped based on ancestral relationships and it has long been used in biology to classify evolutionary relationships between species. Sister species share more recent ancestors compared with other species and are therefore grouped together. Characters are coded according to whether their states are ancestral/primitive or derived/advanced. Based on this character polarity, species that share a similarity of change are grouped to show the phylogenetic classification”

5.3 Fundamentals and concepts of cladistics

Cladistics is one of the techniques or approaches available for data classification and the output is interpreted in the form of a phylogenetic tree.

This phylogenetic tree, specifically called a cladogram, shows the evolution and relationships between entities.

5.3.1 Phylogenetic tree

A phylogenetic tree can be defined as "an illustration of evolutionary relationships among a group of organisms or between collections of "things" (such as genes, proteins and organs), which are derived from a common ancestor" (Ochieng et al., 2007). A phylogenetic tree is very important in illustrating the phylogeny or evolutionary history of an organism (biological environment) or entity (non-biological environment) in order to trace back the lineage relationships between ancestors and other organisms or entities. The term systematic was born from the proper reconstruction of a phylogenetic tree which is capable of showing the distribution and diversity of ancestors and their descendants.

Cladistics and cladograms are grounded in a few principles such as phylogeny, congruence and parsimony (Rakotobe-Joel et al., 2002). Rakotobe-Joel et al. (2002) state that "the philosophical foundations of cladistics focus on the search and selection of shared and derived characters that are used to identify the common ancestry relationships between different configurations. The construction of these relationships produces a cladogram (Figure 5-1) that orders different configurations as a hierarchical system (the classification based on common ancestry (phylogenetic analysis)). Thus, a cladogram is a branching diagram assumed to be an estimate of the relationships between the configurations under study and the final output of a cladistics analysis. The principle of congruence states that a classification should provide internal consistency, i.e. the characters used for a classification should provide one unique phylogenetic relationship, assuming that the configurations are derived from common ancestors. Finally, the principle of parsimony requires that ad hoc assumptions should be minimised as far as possible when explaining natural phenomena. Thus, from all the theoretically possible cladograms, the simplest one is chosen, i.e. the one with the minimal number of nodes (evolutionary changes)." The minimal number of nodes (evolutionary changes) is also referred to as parsimony. ElMaraghy et al. (2008) define parsimony as minimum steps or changes of character state in a tree. The number of steps in the cladogram represents the length of tree, and the simplest or the shortest tree provides better taxa or configurations relationships.

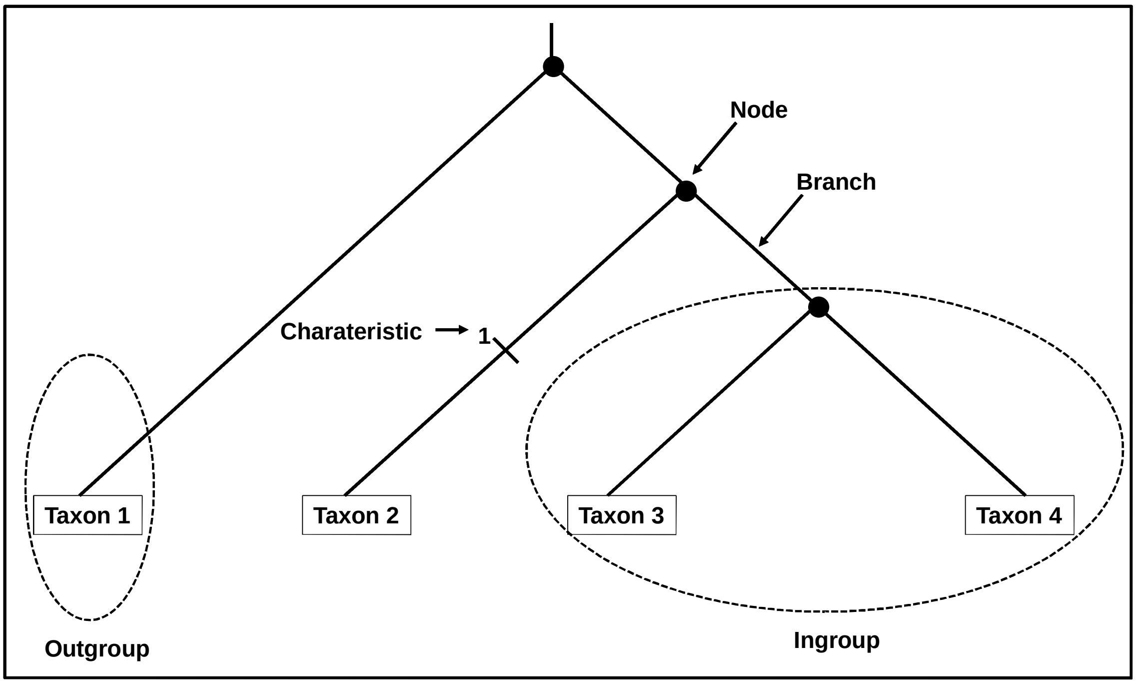

Figure 5-1 A cladogram

Outgroup is a taxon outside the group or subject of interest. Meanwhile ingroup can be defined as a set of taxons or taxa which are more closely related to each other than any are to the outgroup. A node or a branch point on the tree represents the common ancestors of those descendants. Branch is described as a line connecting a branch point node to the other nodes. A taxon (plural: taxa) is a set of organisms or groups of organisms under study.

5.3.2 Major methods to construct trees

There are a number of methods to estimate or construct trees and all of them have their own advantages and disadvantages. There is no limit on which method can be used because the choices are based on situational and current requirements. Furthermore, Hall (2008) states that "it is essential to understand that 'the right tree' does not exist."

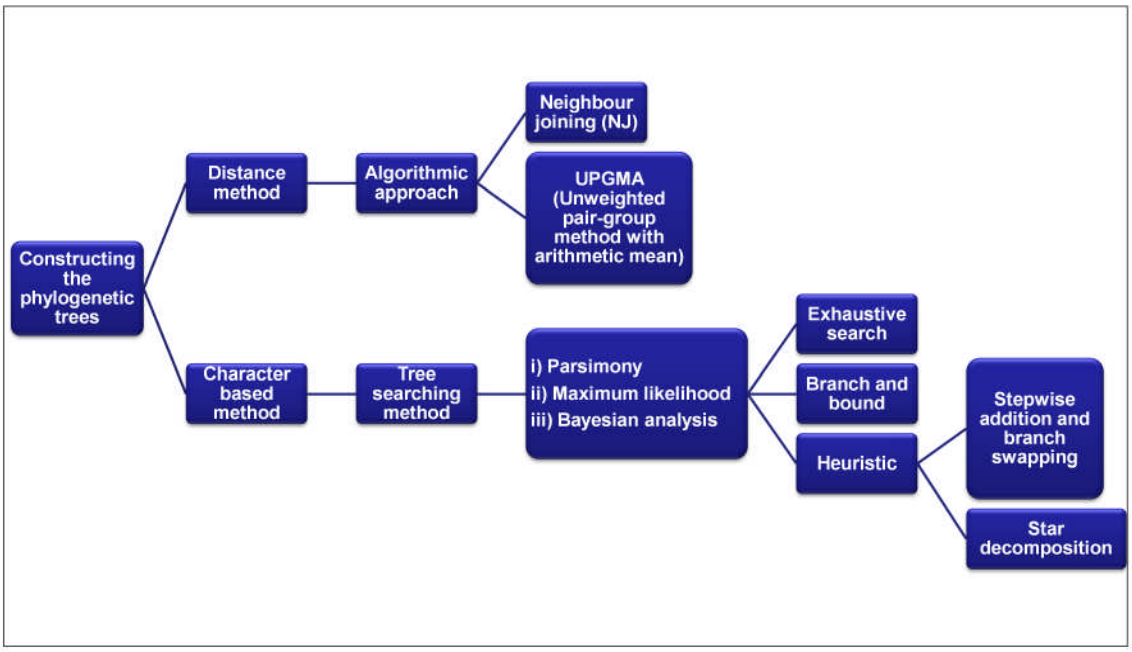

Figure 5-2 Methods to construct the trees

Normally biologists in the molecular and biochemical environment construct the trees for protein, DNA and nucleic acid sequence data using two main approaches: i) distance method; ii) character based method, as shown in Figure 5-2. Hall (2008) describes that "distance methods convert aligned sequences into a distance matrix of pairwise differences (distances) between the sequences." In this approach, the distance for each pair of taxa or fraction of differences between the aligned sequences of taxa is calculated as a matrix. Based on the matrix, branch lengths and branch order are computed as a tree. Since this method uses specific algorithms for the calculations and generating trees, it is normally categorised as an algorithmic approach. Distance based method includes neighbour joining (NJ) and unweighted pair-group method with arithmetic mean (UPGMA).

The character based method focuses on comparing characters between each column or each site. This method generally consists of parsimony, maximum likelihood and Bayesian analysis, and uses an approach called tree searching in constructing the trees. This approach produces many trees and an optimality criterion is used to decide the best tree or best group (set) of trees. The optimality criterion is normally based on the size of data or number of taxa. A few options are available for the optimality criterion such as exhaustive search, branch and bound, and heuristics. Exhaustive search is used when the number of taxa is small. Furthermore, Maddison and Maddison (2005) report that exhaustive search is suitable for data with less than 12 taxa. Ten taxa will produce more than 34 million trees and in this situation exhaustive search is no longer relevant and the best optimality criterion to be used is branch and bound. When the number of trees is becoming larger, a heuristic criterion is used because the branch and bound would take a long time to evaluate each tree and this would slow down the process of getting the best trees, especially in calculating the tree length for all trees. Hall (2008) has reported that “a heuristic approach is essentially a hill-climbing algorithm in which an initial tree is selected, then rearrangements are sought that improve the tree”. Heuristic algorithms are massive but the commonly used algorithm is stepwise addition, branch swapping and star decomposition.

Maddison and Maddison (2005) argue that “likelihood methods use just a measure of a tree, and choose that tree or trees with the highest value of the likelihood, that is, for which the probability of generating the observed data is highest.” The likelihood of the tree is based on the branch lengths and the method is used mostly on DNA and molecular data.

In addition, Hall (2008) states that “Bayesian inference is based on the notion of posterior probabilities: probabilities that are estimated, based on some model (prior expectations), after learning something about the data”. He also adds that Bayesian analysis is “a recent variant of maximum likelihood. Instead of seeking the tree that maximises the likelihood of observing the data, it seeks those trees with the greatest likelihoods given the data. Instead of producing a single tree, Bayesian analysis produces a set of trees with roughly equal likelihoods. The results of a Bayesian analysis are easy to interpret because the frequency of a given clade in any set of trees is virtually identical to the probability of that clade.” This method is also widely used on DNA and molecular data.

This research focuses on constructing trees using the parsimony method. This method has been used widely in the biological environment to identify the relationships between species, especially in plants or animals, based on established morphological characteristics. In other words, biologists deal with form, structure, shape, behaviour or physical characters of plants and animals in order to classify the evolution and relationships of those organisms. Since this research is working on problems and their characteristics in assembly lines, parsimony has been chosen as the best method to construct the trees.

5.3.3 Parsimony

“A cladogram length is the number of steps appearing on the cladogram, which is the total number of character state changes necessary to support the relationship of the taxa in a tree. Fewer steps mean better cladograms with fewer assumptions, better representative hypothesis of the taxa relationship, or what is referred to as ‘parsimony’. The objective of cladogram construction is to generate cladograms with the minimum length (best parsimony)” (AlGeddawy and ElMaraghy, 2010a). This statement shows how the parsimony method has been used in order to generate a tree called a cladogram. This method is based on the assumption that the best tree is a tree with fewer total numbers of changes of character state from 1 to 0 or vice versa. In the other words, the best tree or the most parsimonious is generated based on the shortest tree length. In addition, the shortest tree length will be considered to have fewer homoplasies which are discussed in more detail in the next section.

Maddison and Maddison (2005) also argue that the parsimony method is used to generate scientific hypotheses based on observed data. In the parsimony method, an optimality criterion is used to further confirm that the proposed trees are those meeting the tree length objective function.

5.3.4 Tree terminology

This section discusses the terms and theoretical background of phylogenetic trees, especially the cladogram.

<u>Basics of a tree</u>

"A cladogram is tree-like in appearance. This tree structure represents the evolutionary history, the diversity and the relationships between different manufacturing forms. The network of branches on the tree is the evolutionary paths that have accompanied organisational change programmes. Each path is formed according to the acquisition and polarity of certain characters (manufacturing characteristics that can be new technology, working practices, plant layout, etc.)" (Tsinopoulos and McCarthy, 2000).

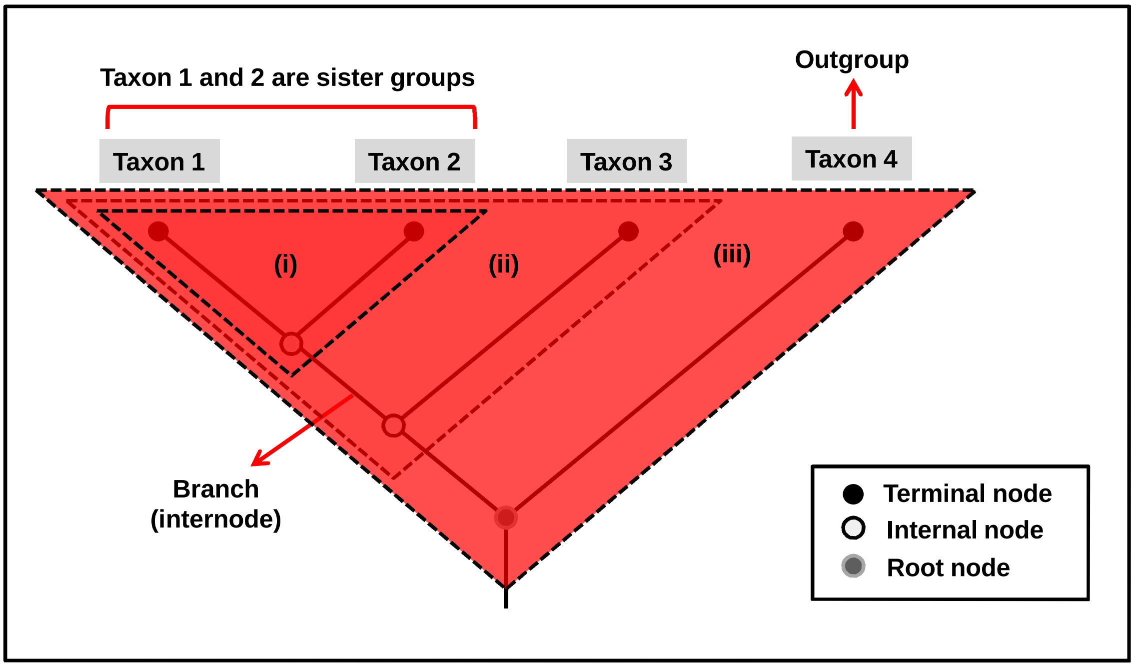

Figure 5-3 Terms in phylogenetic tree (cladogram)

Figure 5-3 shows some specific terms used in a cladogram. A set or group of entities is called a taxa and one entity of that group is called a taxon. Maddison and Maddison (2005) define a taxon as "one or a group of species (or genes, or other entities), and might be either a clade in your tree, or a taxonomic unit placed in terminal position on the tree (a terminal taxon, or Operational

Taxonomic Unit (OTU)”. In addition, Mayr (1969) and McKelvey (1982) define a taxon (singular) or taxa (plural) as “a taxonomic group that is sufficiently distinct to be worthy of being distinguished by name and to be ranked in a definite category.”

Apart from that, the end point of the lineage branches is called a node. There are three types of node: i) terminal; ii) internal; and iii) root. Terminal nodes are placed at the ends or tips of the branches which have no descendants. Terminal nodes are also corresponding to entities or a taxon. Internal nodes are referred to as the branching points and the branches between the nodes are called internal branches. The starting point of the lineage branches is called a root node.

Taxons 1 and 2 are called sister taxa because they are more closely related to each other and share most of the characters from common ancestors. Outgroups can be referred as entities that are not included in the group under study. In addition, Figure 5-3 shows clade in the cladogram (highlighted areas). Tsinopoulos and McCarthy (2000) define the definition of clade in terms of biological and manufacturing contexts. Biologists have defined a clade as “a group of organisms that exists in nature as a result of evolution and includes an ancestral species (i.e.) and all of its descendants. The members of the clade share a set of common ancestry relationships not shared with any other species placed outside the group”. In the context of manufacturing, the term clade can be defined as “a group of manufacturing organisations that exists in an organisational environment (market segments, geographical departments, etc.) and includes an ancestral organisational species (i.e. a form of organisation) that exists through generations which are members of the species. The organisations included in the clade share a set of common ancestry characteristics (automation, quality circles, preventive maintenance, etc.) not shared with any other species placed outside the group” (McKelvey, 1978).

Position of taxon

A tree can be drawn in many ways and the branches can be positioned or rotated without changing or giving a different meaning and interpretation. The ancestors and descendants are still connected even though the positions of taxa have changed, as illustrated in Figure 5-4.

Polytomy (starburst) and dichotomy

Dichotomy or dichotomous refers to a node which has two branches or descendant lineages, while polytomy or polytomous refers to a node with more than two branches or descendant lineages, as shown in Figure 5-5 (Maddison and Maddison, 2005). Polytomy represents unresolved nodes because it shows uncertainty in relationships due to lack of information between taxons. Apart from that it may also represent “multiple simultaneously branching” because each taxon is closely related to each other (Maddison and Maddison, 2005).

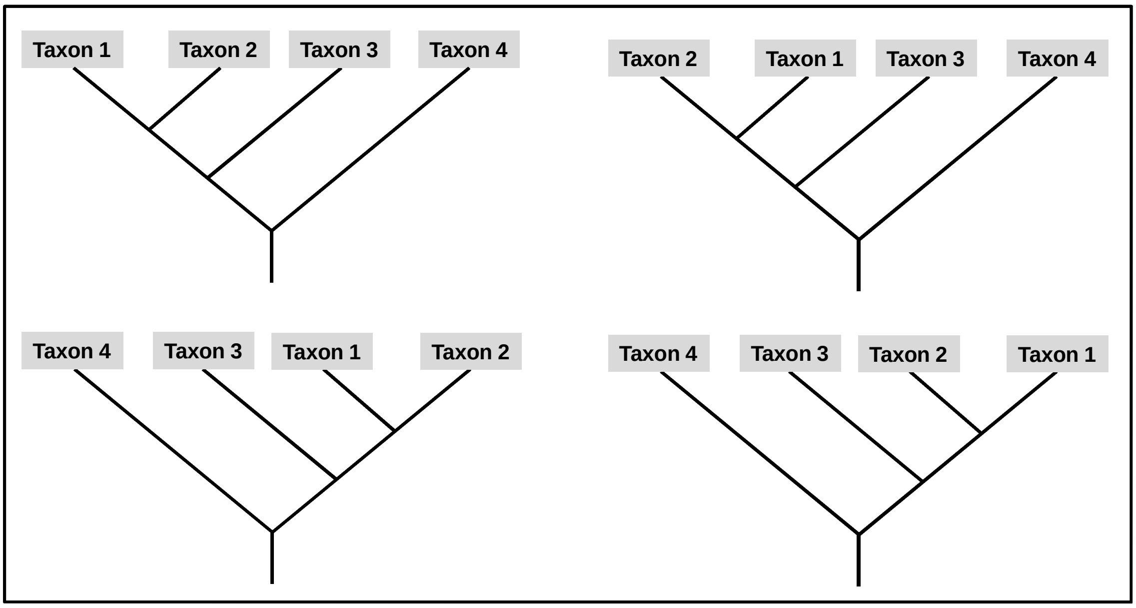

Figure 5-4 Positions of taxa

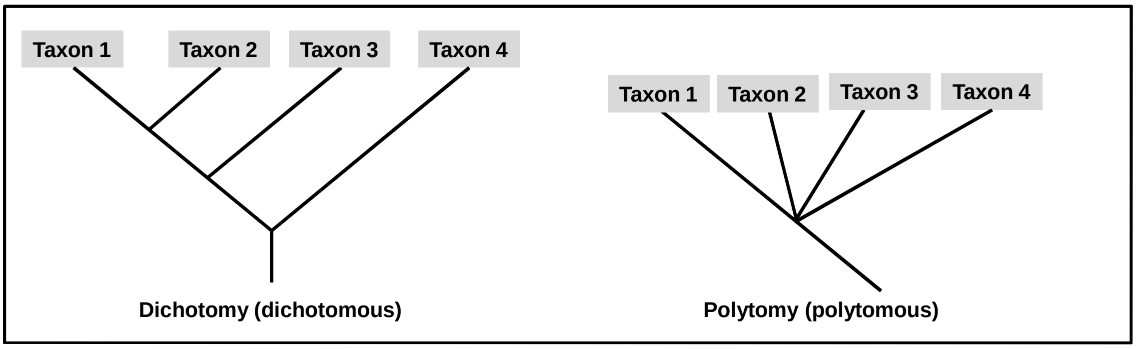

Figure 5-5 Polytomy and dichotomy

Homology and homoplasy

The term homologous or homology is used when two species or entities have inherited similar characteristics from their common ancestor, while analogous or homoplasy refers to unrelated species or entities which have similar characteristics due to convergent evolution. In other words, the two different species have a characteristic which has a similar function that resembles each other due to the adoption of a similar way of life.

Plesiomorphic and apomorphic characters

One of the important steps in evolutionary analysis is to identify which character states are plesiomorphic (primitive) and apomorphic (derived). Commonly the plesiomorphic (primitive) state is given as 0 and apomorphic (derived) state as 1. Figure 5-6, condition (i), shows that the character state for “b” is plesiomorphic (primitive) and inherited from the ancestor. It is assumed that the character state for “b” evolved once and the character state for “a” evolved twice, i.e. in taxon 3 and the outgroup. Figure 5-6, condition (ii), shows that both character states for “a” and “b” evolved only once. Therefore condition (ii) is the most parsimonious because it has the lowest number of changes in terms of character state and the hypothesis is more defensible due to fewer assumptions.

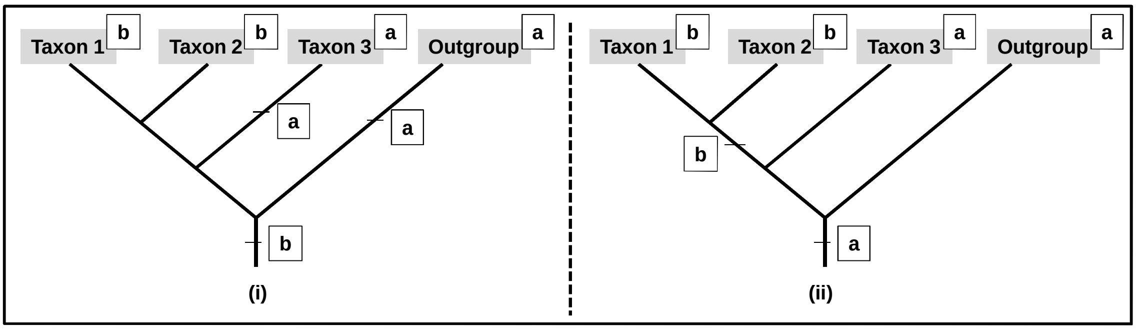

Figure 5-6 Plesiomorphic, apomorphic and parsimony

5.3.5 Building the cladogram

The basic steps in constructing a cladogram have been adapted from the classic biological area (Rakotobe-Joel et al., 2002; Tsinopoulos and McCarthy, 2000). Rakotobe-Joel et al. (2002) describe the framework for constructing the cladogram as consisting of four stages as given below:

Step 1: Selecting the taxa or clade

The first point that needs to be prioritised is to define the taxa or clade. In other words, identifying what is the subject to be classified or studied. Generic labels can be used for the taxa or clade and its characteristics, as shown in Table 5-2. In the context of this research, the configurations column is represented by the problems established from the reviewed papers. In the character states column: 0 means that the configuration does not possess the character and 1 means that the character exists.

Table 5-2 Matrix table for cladogram development (source: Rakotobe-Joel et al., 2002)

Configurations	Characters									
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
F1	0	0	0	0	0	0	0	0	0	0
F2	0	0	0	0	0	0	0	0	1	1
F3	0	0	0	0	0	0	1	1	1	1
F4	0	0	0	0	0	1	1	1	1	1
F5	0	0	1	1	1	1	1	1	0	1
F6	1	1	1	1	1	1	1	1	1	1

Step 2: Determining the characteristics

“Initially the complete membership and the diagnostic characteristics of the clade are not necessarily known, and for both biological and non-biological systems the problem is determining those characters that are cladistically valuable from the set of all potential characters. For example, with the organisational cladogram, evidence should be sought to maintain the assumption that the characters selected will infer and represent descent from common ancestors. Consequently, the aim of this step is to review the history of the entities and to find evidence that will represent the pattern of historical relationships for the selected taxa. For social and technological entities, this evidence tends to be in the form of published material or archives, which can be systematically assembled to produce a data matrix. The matrix indicates which characters have been selected and how they are coded for cladistic analysis.” (McCarthy, 2005).

Rakotobe-Joel et al. (2002) also argue that the initial relationship between a set of taxa or clade is considered to be polytomy because no relationships have been established between these entities, as shown in Figure 5-7.

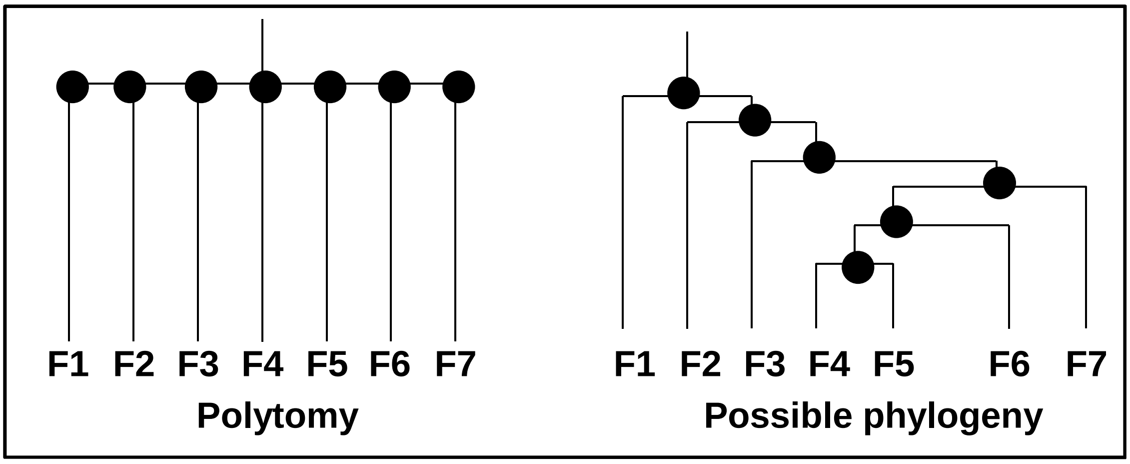

Figure 5-7 Polytomy and phylogeny (source: Rakotobe-Joel et al., 2002)

Step 3: Characters and its states

Once the configurations (taxa or clade) and their characteristics have been identified, the matrix table can be developed, as shown in Table 5-2. The figures 0 and 1 represent the states of the characteristics; 0 means that the characters do not exist in the configurations or primitive and 1 means that the characters do exist or are derived.

Step 4: Cladogram development

McCarthy (2005) argues that the Hennig Argumentation method has been recognised as the main approach for developing or constructing a cladogram. Simple data can be manually constructed but if the data set is large and complex, phylogenetic software is used to identify the evolutionary relationships between the taxa or clades. One of the softwares or tools available is MacClade. The Hennig Argumentation method analyses each character based on Table 5-2, as shown below:

- Table 5-2 consists of 10 characters and 6 configurations (taxa/clade). Initial relationship is considered polytomy as shown in Figure 5-8 (a)

- Characters C1 and C2 exist in configuration F6 (see Figure 5-8 (b))

- Characters C3, C4 and C5 are shared by configurations F5 and F6 (see Figure 5-8 (c))

- Character C6 is shared by configurations F4, F5 and F6 (see Figure 5-8 (d))

- Characters C7 and C8 are shared by F3, F4, F5 and F6 (see Figure 5-8 (e))

- Characters C9 and C10 are shared by configurations F2, F3, F4, F5, and F6 (see Figure 5-8 (f))

Figure 5-8 (f) shows that F1 is an outgroup and has no relationship with the other groups of configurations. Character C10 unites all configurations (F2-F6) except F1 because they share the apomorphic (derived) state. Characters C1 and C2 are called autapomorphy because they are found only in F6. Meanwhile, Characters C3, C4 and C5 are called synapomorphy or shared derived character states because they are shared by configurations F5 and F6. There is a conflict between character C9 and configuration F5. It is assumed that character C9 reverses to state 0 in configuration F5. Therefore, one homoplasious step (one reversal) is required in order to build the most parsimonious tree. In the case of homoplasious for convergence, it is assumed that one character needs to be available in two configurations or taxa.

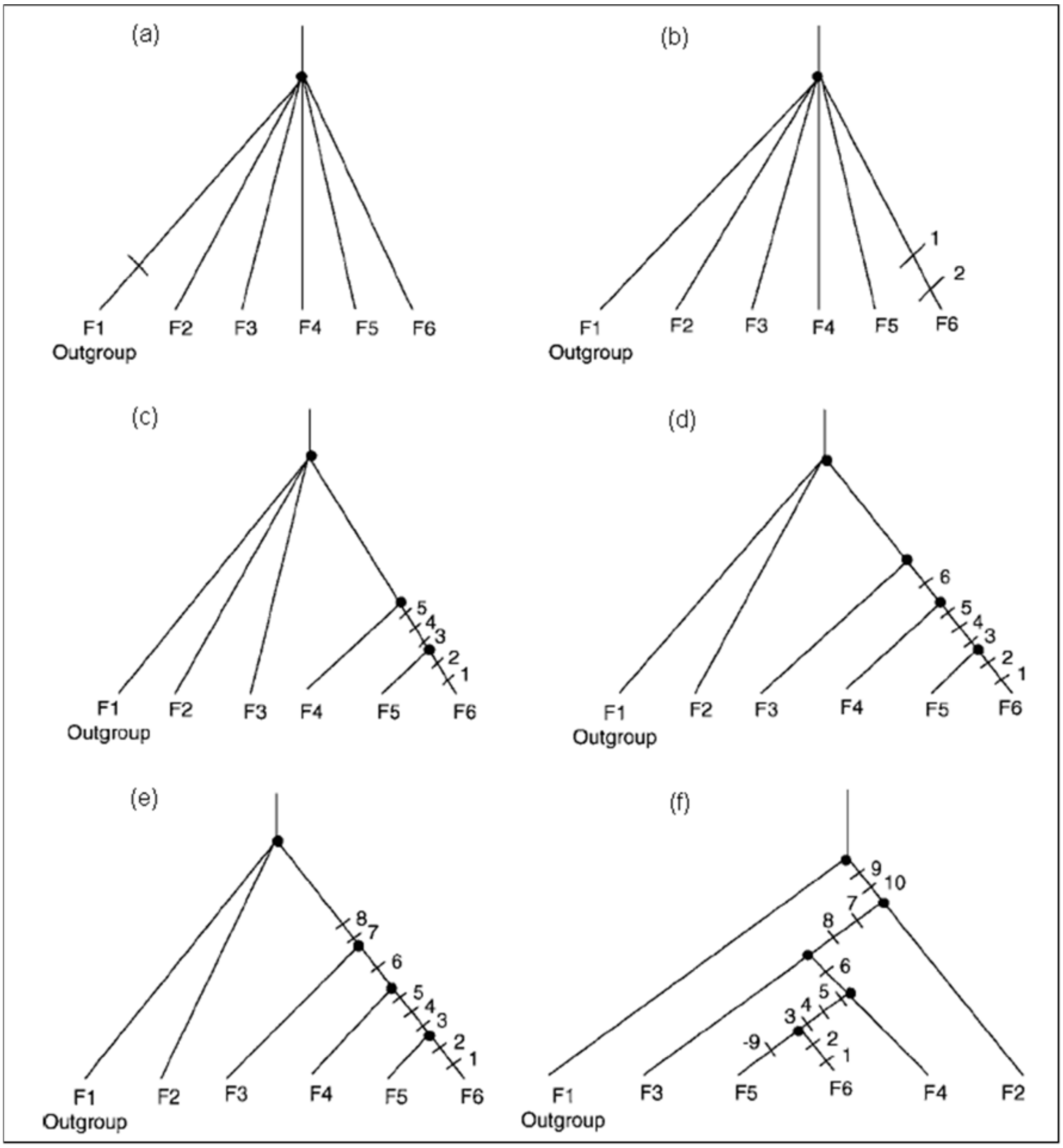

Figure 5-8 Constructing a cladogram (source: Rakotobe-Joel et al., 2002)

In addition, McCarthy et al. (1997) and Tsinopoulos and McCarthy (2000) have also established a framework for constructing the cladogram consisting of seven stages, as given below:

<u>Stage 1: Identify the clade or taxa</u>

This stage defines the subject to be studied. In this research the problems established in assembly lines are referred as clades. Clade is defined as “a group of organisms that exists in nature as a result of evolution and includes an ancestral species (i.e.) and all of its descendants. The members of the clade share a set of common ancestry relationships but not shared with any other species placed outside the group" (Tsinopoulos and McCarthy, 2000).

McCarthy et al. (1997) also agree that the starting point in building a cladogram is to define the subject or clade that will be studied.

Stage 2: Identify the characters

This stage focuses on identifying the characteristics for each problem. In this research, causes of the problems will be the characters for each problem.

McCarthy et al. (1997) report that this stage focuses on determining the characters and their states. The character states can be defined as "a condition that this feature exhibits". There are three types of character: i) conflict; ii) consistent; iii) congruent. The relationships between these characters are shown in Figure 5-9. Characters 1 and 4 are shared by entities 1, 2 and 3. Characters 1 and 4 are congruent. Character 3 is shared by entities 2 and 3. Character 2 is present in entities 4 and 5. Character 5 presents in entities 3 and 5 and conflicts with the two main clades which are groups of entities (1, 2 and 3) and (4 and 5). McCarthy et al. (1997) also report that "a conflicting character does not agree with the grouping suggested by another character". Character 5 has arisen twice in entities 3 and 5. It is assumed that this character is convergent in those entities or taxa. In other words, one homoplasious step (one convergence) is required in order to build the most parsimonious tree. Characters 3 and 2 are consistent. "Two characters are said to be congruent if they confirm the exact same groupings, whilst a consistent character is one which conforms with another character because its position on a separate branch of the cladogram does not refute the groupings." (McCarthy et al., 1997).

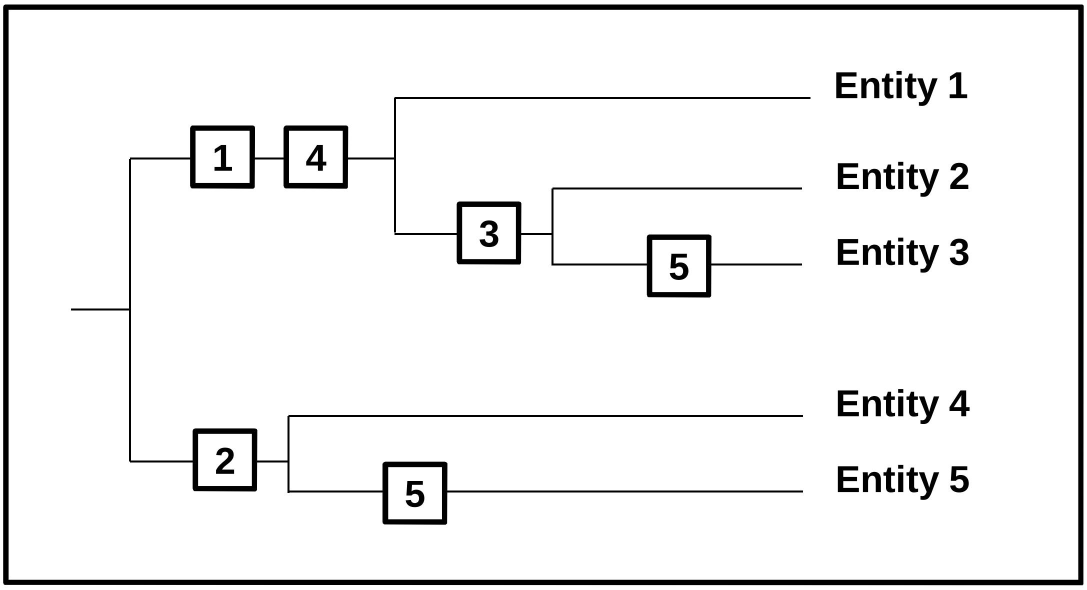

Figure 5-9 Characters and relationship

<u>Stage 3: Code characters</u>

In this stage, the relationship between the clades (problems) and characteristics will be examined in order to construct the cladogram.

<u>Stage 4: Establish character and polarity</u>

This stage concerns determining whether the characters are primitive or derived. Primitive is defined as “those characteristics which are present in an ancestral species” and derived is defined as “those characters which are not present in an ancestral species.” (Tsinopoulos and McCarthy, 2000).

<u>Stage 5: Construct cladogram</u>

In this stage, a cladogram is constructed based on data already collected. Specific tools to construct the cladogram will be used in order to find the best estimate of the evolutionary relationship based on data matrix established.

<u>Stage 6: Consensus tree</u>

The aim of this stage is to validate the proposed tree by ensuring that the clades (problems) and characteristics are correctly assigned in a tree structure.

The output of this stage will be used to verify the output from the previous stage. Most of the publications and research works that implement cladistics in manufacturing organisations only focus on studying real and existing subjects to be studied through plant inspection, assessment of documentation, assessment of procedures and interviews with employers or employees in order to validate the tree or cladogram constructed. Those methods can be used to validate the established cladogram.

For biologists who have found new species of animals or plants, it is hard for them to validate the established cladogram based on the above approach because the new species do not exist yet. Multiple trees generated by the phylogenetic tools create uncertainty in evolutionary (phylogenetic) relationships because users may obtain exactly the same result even though the trees are constructed using same process and ancestral. Due to the conflicts, finding the consensus trees through specific mathematical calculation is the best solution in this case.

Stage 7: Taxa nomenclature

This stage focuses on naming the clades or taxa established at the branches of the tree.

5.3.6 Descriptive statistics

There are three descriptive statistics available for the established cladogram: tree length, consistency index and retention index (McCarthy, 2005). The tree length refers to the total number of steps established in constructing the cladogram. Fewer steps mean fewer evolutionary changes (character state changes) and this is called the best or the most parsimonious tree (ElMaraghy et al., 2008). If the cladogram fits the data, it requires a minimum number of homoplasies (reversal or convergence) steps and character state changes so is more parsimonious. Hall (2008) has defined homoplasies as “extra steps or hypotheses that are required to explain the data.”

“Parsimony is based on the assumption that the most likely tree is the one that requires the fewest number of changes to explain the data. The basic premise of parsimony is that taxa sharing a common characteristic do so because they inherited that characteristic from a common ancestor. When conflicts with that assumption occur (and they often do), they are explained by reversal (a characteristic that changed but then reverted to its original state), convergence (unrelated taxa evolved from the same character independently), or parallelism (different taxa may have similar properties that predispose a characteristic to develop in a certain way)” (Hall, 2008)

Based on Table 5-2 in Section 5.3.5, Figure 5-10 (a) shows that the tree length is 11 (11 characters state changes) and Figure 5-10 (b) shows that the tree length is 18 (18 characters state changes). Therefore the shortest or the most parsimonious tree is Figure 5-10 (a).

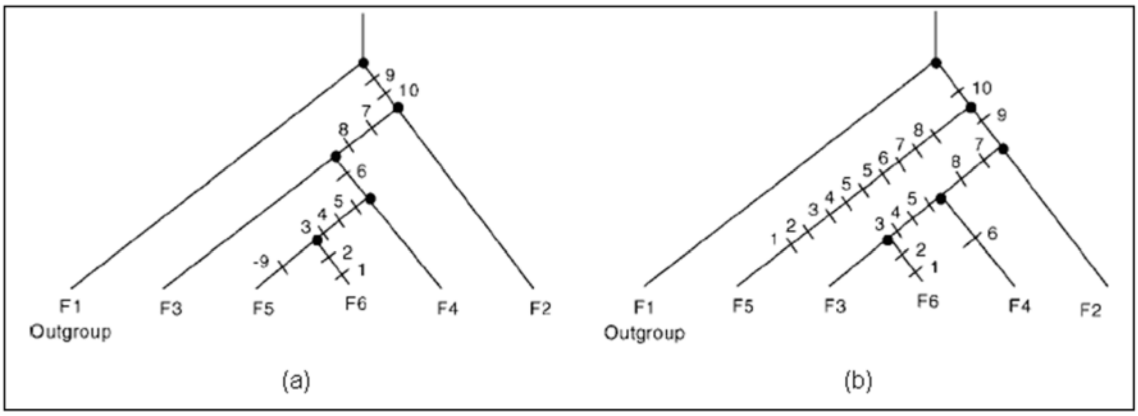

Figure 5-10 Tree length (source: Rakotobe-Joel et al., 2002)

Rakotobe-Joel et al. (2002) define the consistency index (CI) as “the level of difficulty in fitting a data set to a cladogram” and is given by:

$$CI = M / S \tag{5-1}$$

Where M is the total number of expected character changes and S is the tree length. A perfect fit between the data and cladogram is indicated by the CI of 1.

Apart from that, retention index (RI) is defined as “the proportion of synapormophy (shared and derived characters) in a cladogram” (Rakotobe-Joel et al., 2002). The RI is calculated using the formula:

$$RI = (G - S)/(G - M) \qquad \textbf{(5-2)}$$

Where S and M are the same variables used by CI and G is the total number of configurations with state 1 or 0 (whichever is smaller). The better the tree, the closer RI is to 1.

Based on Table 5-3, the RI is calculated as:

RI = (18 - 11)/ (18 - 10) = 0.875

Table 5-3 Information used for retention index calculation (source: Rakotobe-Joel et al., 2002)

	Characters									
Configurations	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
F1	0	0	0	0	0	0	0	0	0	0
F2	0	0	0	0	0	0	0	0	1	1
F3	0	0	0	0	0	0	1	1	1	1
F4	0	0	0	0	0	1	1	1	1	1
F5	0	0	1	1	1	1	1	1	0	1
F6	1	1	1	1	1	1	1	1	1	1
Max steps (g)	1	1	2	2	2	3	2	2	2	1
										G = ∑g = 18

5.4 Advantages of classification

“A reconstructed phylogeny helps guide our interpretation of the evolution of organism characteristics, providing hypotheses about the lineages in which traits arose and under what circumstances, thus playing a vital role in studies of adaptation and evolutionary constraints” (Ochieng et al., 2007).

McCarthy et al. (1997) report that evolutionary relationship between entities based on the classification or phylogenetic tree generates changes that can help investigators to distinguish the similar and dissimilar among the entities. Since classification is quite important, they also report the purposes of developing the classification as: i) to communicate or to make more clearly comprehensible the subjects under study; ii) to discover new things or research; iii) to construct, arrange or plan a proper structure of entities; iv) check list. They also draw attention to the fact that a classification is very useful for a few reasons: i) it is capable of describing what has been observed; ii) it can predict and provide an explanation on what has not yet been observed; iii) it helps in explaining the evolutionary history of the entities; iv) it generates hypotheses about the relationships among the entities.

Tsinopoulos and McCarthy (2000) state that classification development using evolutionary analysis is considered to be beneficial because it is capable of providing unique and unambiguous information based on a developed cladogram. Apart from that the cladistics technique has great strengths in making decisions transparent, such as representation of classification in the form of tree structure and illustration of data, assumptions and results.

McCarthy and Ridgway (2000) report that classification based on evolutionary relationships is beneficial for several reasons: i) the classification established is unique and unambiguous; ii) cladistics produces a natural and objective classification based on relevant established characteristics and unambiguous entities through evolutionary relationships in the developed cladogram; iii) the developed cladogram provides transparent decisions based on concrete proof of data, assumptions and results.

5.5 Cladistics in a non-biological environment

Previously, cladistics and cladograms were produced based on DNA or genetic sequences and morphological characters in evolutionary biology but now there is a trend to implement this technique of classification in non-biological environments such as manufacturing.

The implementation of cladistics in the manufacturing area has not been extensively reported. In previous years, research on cladistics in manufacturing has tended to focus on organisational configuration such as benchmarking, organisational changes and manufacturing strategies. Tsinopoulos and McCarthy (2000) in their publication presented the use of a cladistics technique in order to systematically manage an organisation and identify current or future possibilities of achievements in agile manufacturing. The summary of some research works related to manufacturing and cladistics is provided in Table 5-4.

Table 5-4 Related works on cladistics and manufacturing

Authors	Focus
Fernandez et al. (2001)	Benchmarking framework for manufacturing organisations especially in automotive assembly plants
Rakotobe-Joel et al. (2002)	Strategic management processes such as strategic analysis, strategic choice and strategic implementation
McCarthy (1995)	Classifying manufacturing organisations for the purposes of organisational design and change
McCarthy et al. (1997)	Manufacturing system classification to identify organisation’s character change, competitiveness and performance
McCarthy and Ridgway (2000)	Identifying the manufacturing characteristics for achieving successful organisational design and change
McCarthy et al. (2000)	Investigating the feasibility of constructing cladistic classification in order to facilitate the development of manufacturing systems
Baldwin et al. (2005)	Modelling manufacturing evolution for transformation, and to identify the differences between sustainable and non-sustainable organisations, and to specify new structures for sustainability
ElMaraghy et al. (2008)	Focusing on evolution of complex changes occurring in manufacturing systems, products and their attributes

Authors	Focus
AlGeddawy and ElMaraghy (2009)	Identifying a biological framework and model through cladistics aimed at enhancing the design process of product and manufacturing systems
AlGeddawy and ElMaraghy (2010a)	Introducing a design methodology for delayed product differentiation using the cladistics technique in assembly lines' layout
AlGeddawy and ElMaraghy (2010b)	Co-evolution hypotheses and model for manufacturing planning
AlGeddawy and ElMaraghy (2011)	Focusing on a knowledge discovery model in order to capture and manage relationships between product features and manufacturing capabilities for new products
Rose-Anderssen et al. (2009)	Addressing the advantages and potential benefits of the cladistics technique as an evolutionary analysis tool for commercial aerospace supply chains
Rose-Anderssen et al. (2011)	Focusing on empirical validation of developed classification scheme and providing a framework which includes the diversity of evolution in the supply chain

Currently, there is a trend towards implementing cladistics in production systems, products and processes, as with previous studies (e.g. Tolio et al., 2010), where cladistics is used as a tool to support the development of a modelling framework based on the coordinated evolution of production systems, processes and products in order to increase the life cycle of the three components. In addition, ElMaraghy et al. (2008) deal with modelling the evolution of products and their production systems. The objective of their research is to capture the complex changes in products and manufacturing systems in order to manage the evolution effectively. Furthermore, AlGeddawy and ElMaraghy (2009) have presented a biological framework and model through cladistics aimed at enhancing the design process of product and manufacturing systems so as to manage the product changes in an efficient way. AlGeddawy and ElMaraghy (2010a) also introduced a design methodology which focusing on assembly line layout for delayed product differentiation and the cladistics technique is used by them for product commonality analysis.

McCarthy et al. (1997) focus on investigating the benefits of cladistics classification in manufacturing systems and technology management. Their research shows how the cladogram has been developed, the evolution of a group in manufacturing systems and what is similar and dissimilar among the entities being studied, based on established classifications. In addition, the rules and guidelines on validating and analysing the cladogram are also provided.

McCarthy and Ridgway (2000) point out a few benefits of cladistics in manufacturing organisations:

- “This framework (cladogram) could help companies to clearly identify the manufacturing characteristics which are appropriate for their industry and business needs, and to help companies identify their position relative to the desired position”
- “This framework (cladogram) will provide insights into manufacturing change which can systematically be applied to the planned development and reinforcement of organisational structures, technologies, strategies, and processes for improving a manufacturing organisation’s effectiveness”
- “The cladogram provides knowledge which could enable the formulation of clear and fitting action for either best practise imitation (mimetic strategy) or the innovation of a new manufacturing form (normative strategy)”
- “A cladistics classification of manufacturing organisations could provide a system for conducting, documenting and co-ordinating comparative studies of manufacturing organisations. Such a system could provide the consensus for formally approving, validating and typifying the emergence of new manufacturing forms”
- “The cladogram would represent the contours of change for a manufacturing industry, thus providing knowledge and observations on

> the patterns of the distributed characteristics exhibited by manufacturing organisations over their evolutionary development"

In the context of this study, cladistics is used to show the evolution of problems related to assembly lines, the related constraints that need to be considered, and from where the problems originated through a diagram called a cladogram. The evolution of problems through a cladogram can be used as a guideline for modellers in model building and simulation, especially in providing the common and specific elements required for performance measures so as to reduce the model development time.

5.6 Classification established

This stage is called "Stage 2", as illustrated in the research methodology in Figure 3-1 in Chapter 3. At this stage, a cladogram is developed based on the problems collected in "Stage 1". The intention is to build a classification scheme and to carry out an analysis of the problems and their evolution. The evolution of problems can be distinguished effectively through the cladogram.

Table 5-5 shows that 27 problems have been collected from the reviewed papers. The most common problems that have been reported are high operating cost, low throughput rate, long lead time, high WIP and bottlenecks. The rest of the problems are related to assembly line balancing problems (ALBs) which consist of five main groups: i) ALBs 1 to 4 (related to workpiece and movement); ii) ALBs 5 to 9 (related to product model); iii) ALBs 10 to 13 (related to reconfiguration of resources); iv) ALBs 14 to 16 (related to parallelisation); v) ALBs 17 to 22 (related to assignment of resources to operations/tasks).

Table 5-5 Problems established from the reviewed papers

	List of problems
1	High operating cost
2	Low throughput rate
3	Long lead time
4	High WIP
5	Bottleneck
6	ALB 1
7	ALB 2
8	ALB 3
9	ALB 4
10	ALB 5
11	ALB 6
12	ALB 7
13	ALB 8
14	ALB 9
15	ALB 10
16	ALB 11
17	ALB 12
18	ALB 13
19	ALB 14
20	ALB 15
21	ALB 16
22	ALB 17
23	ALB 18
24	ALB 19
25	ALB 20
26	ALB 21
27	ALB 22

Table 5-6 shows the characteristics established for the problems related to high operating cost, low throughput rate, long lead time, high WIP, bottleneck and assembly line balancing. There were 91 characteristics that had been extracted based on the 27 main problems identified. Four characteristics have been excluded from those shown in Table 5-6: i) 6; ii) 12; iii) 16; iv) 20. These characteristics were no longer relevant due to their similarity to others.

Table 5-6 Characteristics established from the reviewed papers

	List of characteristics
1	Lines not balanced
2	Buffer size and location
3	Number of stations
4	Long lead time
5	High WIP
7	Low productivity
8	Machine breakdown
9	Number of products
10	Bottleneck
11	Imbalance of cycle time (processing time)
13	Parts reject/rework
14	Batch size
15	Number of setups
17	Blockage and starvation (downstream stations are idle and upstream stations are blocked)
18	Low throughput rate
19	High setup time
21	Long distances between stations
22	Long waiting time
23	Workpiece and movement
24	Paced line
25	Operations start at same time, parts move at the same rate
26	Fixed cycle time
27	Station time less than determined cycle time
28	Station may idle
29	Station idle time will increase
30	Continuous transportation of workpiece
31	Movement rate is too slow and greater than cycle time
32	Stations' length
33	Movement rate of the lines
34	Operations could not be completed in time
35	Unpaced line
36	Asynchronous
37	All workpieces are moved whenever the required operations are completed (workpieces are transferred individually)
38	Buffer installation cost
39	Synchronous
40	All stations pass workpieces simultaneously
41	All stations wait for the slowest station to finish its operations before workpieces are transferred at the same point in time
42	Cycle time is determined by the slowest station
43	Product model
44	Single product model
45	High volume production of a single product

	List of characteristics
46	No variation of products
47	Does not require more than one set-up
48	No variations in operating times
49	Mixed product model
50	Different product models are manufactured in the same production system
51	Production processes are quite similar (homogeneous production processes)
52	Setup times are assumed not present (negligible)
53	Small variations in products features (attributes)
54	Variations in process times due to variations of features (attributes)
55	Reducing the allocation of operations or tasks at the same station
56	Overload (required cycle time has been exceeded)
57	Assignment of resources (equipment selection) to operations/tasks
58	Similar operations/tasks which are performed on different models are always assigned to the same station
59	Installation of identical resources
60	Duplication of stations/machines
61	Assignment of identical operations/tasks to different stations (parallel operations/tasks in the lines)
62	Multi/batch model
63	Different models are manufactured in batches
64	Different batches are manufactured using same resources
65	Manual labour
66	Work content (station load) of an operator could be changed subject to any new batch
67	Changes in work content may reduce level of specialisation among the labourers
68	Additional trainings are required
69	High scrap/waste
70	Reconfiguration of resources
71	Rearrangement of resources to the new structure of production lines
72	Assignment of resources (equipment selection) to operations/tasks
73	Minimise the number of stations for a given cycle time
74	Minimise the cycle time for a given number of stations
75	Re-allocation of heavy machinery
76	Position changed
77	Movement cost
78	Limitation of space available
79	Position unchanged
80	Sequence or re-sequence of tasks/operations
81	Manual labour re-allocation
82	Parallel lines
83	Number of lines that need to be installed
84	Assignment of labourers to tasks/operations or stations
85	Parallel tasks/operations

	List of characteristics
86	Parallel stations
87	Multiple labourers (more than one labourer is assigned to a station)
88	Equipment and facility cost
89	Labour cost (extra wages)
90	Incompatibility between tasks/operations at the same stations
91	Availability of workpiece
92	Workpieces may not be ready for the next tasks/operations in next station due to short distances between stations
93	Resource capabilities and difficulties of tasks/operations
94	Tasks/operations may require high level of skills, experience and qualifications of labourers
95	Difficulties of tasks/operations may require high level technologies of stations/machines

Once the sample data (problems) and characteristics for each problem have been extracted from the reviewed papers, a matrix table is created in MacClade. The matrix table consists of three main parts: i) left column: list of problems (entities or taxa); ii) top side: list of characteristics; iii) medium grid to show whether the characteristics are present (state 1) or absent (state 0) in each listed problem. The final matrix table represents the presence or absence of characteristics for each problem under study. The 27 problems established with their inherited characteristics are illustrated in Table 5-7.

5.6.1 Results

The MacClade software analyses and groups the data through statistical analysis in order to produce the most parsimonious tree called a cladogram using the Hennig Argumentation and parsimony method. Based on the established matrix table, a cladogram has been developed, as shown in Figure 5-11.

Three descriptive statistics have been used to validate the established cladogram: length of the tree, consistency index and retention index. The total length of the cladogram is 125 steps which consist of 27 problems and 91 characteristics. The cladogram is the most parsimonious found so far. In this case, the consistency index is 0.73 and retention index 0.56. Since more than

70% of the characteristics and problems fit each other with fewer conflicts in order to produce the most parsimonious tree, the cladogram is acceptable and the quality is good. However, some contradictions have been found based on homoplasies (reversal and convergence) concepts; thus, black triangle symbols appear, indicating that other taxa do possess that characteristic around the branches. In addition, the black rectangular symbol represents unique characteristics which indicate that the characteristic is only available in certain taxa. Each number on the tree refers to a characteristic as listed in Table 5-6.

Table 5-7 Matrix table established

	1									10										20										30										40										50					55
Outgroup	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High operating cost	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Low throughput rate	0	1	0	1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Long lead time	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High WIP	0	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bottleneck	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 3	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0
ALB 6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1	1	1	1
ALB 7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	0	0	0	0
ALB 8	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
ALB 9	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
ALB 10	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 11	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 12	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 13	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 14	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 15	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 16	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 17	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 18	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 19	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 20	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 21	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 22	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	56				60										70										80										90					95
Outgroup	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High operating cost	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Low throughput rate	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Long lead time	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High WIP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bottleneck	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 7	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 8	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 9	1	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 10	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 11	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 12	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 13	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 14	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
ALB 15	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
ALB 16	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0
ALB 17	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
ALB 18	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 19	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
ALB 20	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ALB 21	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0
ALB 22	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1

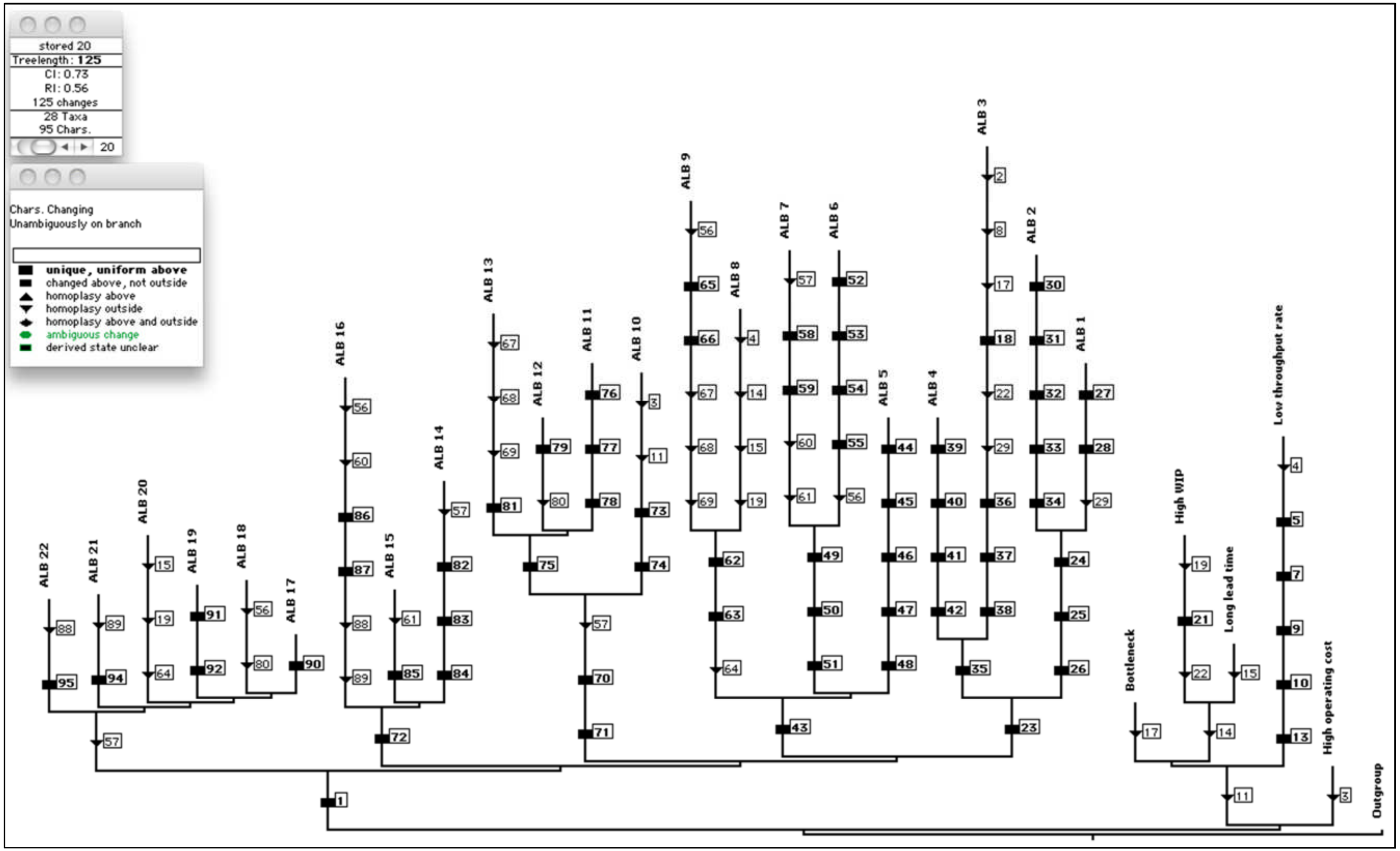

Figure 5-11 Established cladogram

5.6.2 Discussion

It is important to bear in mind that the established cladogram does not show the final key findings. Since the problems and their characteristics are evolved over time, the cladogram will be continuously developed. The cladogram may change subject to new problems and characteristics. Once the cladogram is updated, the library of simulation templates will also be updated. The library is a repository for all templates that can be changed, added or deleted over the time based on the changes of the cladogram.

The established cladogram classifies the evolution of problems in a very useful way. It provides information which covers past and future directions of evolution. Thus, this information can be very helpful to modellers to identify the suitable elements that are required for performance measures and simulation modelling.

Trends and evolution

Figure 5-12 shows another form of established cladogram. In the case of this research, there are six groups of common problems: i) group (i): ALBs 17 to 22 (problems related to assignment of resources to operations/tasks); ii) group (ii): ALBs 14 to 16 (problems related to parallelisation); iii) group (iii): ALBs 10 to 13 (problems related to reconfiguration of resources); iv) group (iv): ALBs 5 to 9 (problems related to product model); group (v): ALBs 1 to 4 (problems related to workpiece and movement); group (vi): problems related to high operating cost, low throughput rate, long lead time, high WIP and bottleneck problem. Groups (i) to (v) are closely related to each other and they are called sister groups of taxa as they share most of their characteristics from the common ancestor. These groups of taxa will have a direct impact on the problems listed in group (vi). The evolution of each problem, based on inheritable changes of characteristics, can be traced using the developed cladogram. The evolutionary path for each problem shows the splitting points of each path and the emergence or reversal of characteristics (homoplasy). Based on the evolution path, the combination of characteristics can be tracked up to the splitting points around the tree. In addition, a clear direction or trend of problems can be observed based on primitive states of characteristics towards more complex derived states of characteristics. In the condition of homoplasy, sometimes reversal condition takes place where derived states (state 1) characteristics need to be transformed to primitive states (state 0) in order to develop the most parsimonious tree and this may affect the evolution trend of problems.

Future trends of evolution

The evolution of problems established in the cladogram, as shown in Figure 5-12, can be used by modellers to envisage new problems or characteristics that might evolve in the future. The established evolutionary paths and splitting points provide useful information regarding the elements required for performance measures in simulation modelling. Apart from that, evolutionary trends among the groups of problems established can be used as an indicator and direction for the future evolution of problems

Enhancing elements for simulation modelling

The relationships of characteristics and established problems is very useful in providing better solutions and preventive measures or actions in the future, especially those related to assembly lines and balancing. Current characteristics that have been visualised in the form of a cladogram can be rearranged, added, changed and deleted along the evolution path based on current problems that need to be tackled. Enhancing the pattern of evolution can help in establishing a properly developed cladogram and streamlining the problem variations with relevant characteristics. A thorough understanding of the evolutionary of problems and their characteristics is very useful in helping modellers to identify the suitable elements required for performance measures in simulation modelling.

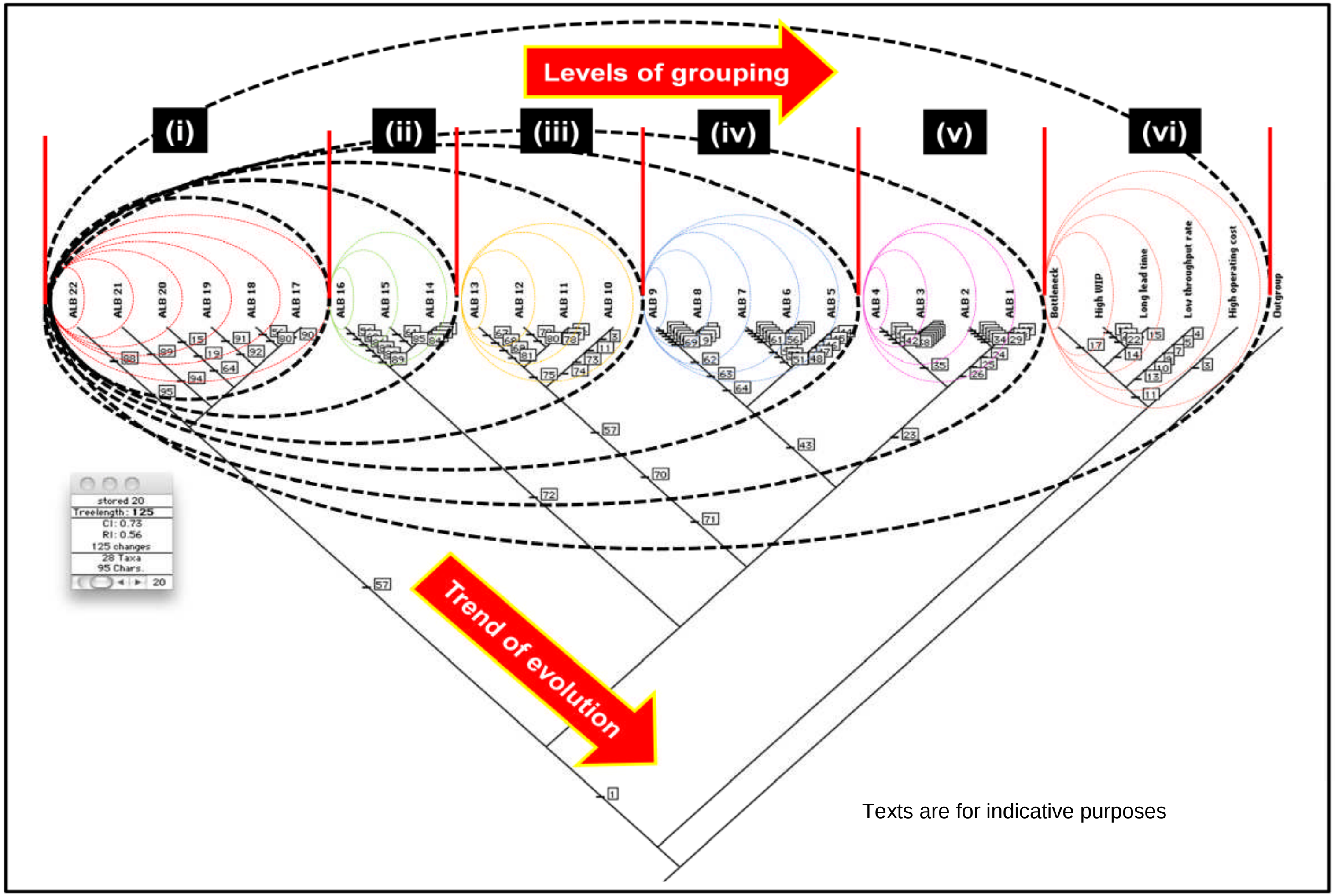

Figure 5-12 Levels of grouping and trends of evolution

Designing solutions and decision for problems

ALB 3 is classified under group (v) in the established cladogram, as shown in Figure 5-13. ALB 3 focuses on movement of workpieces in unpaced asynchronous lines. ALB 3 possesses many derived and primitive characters: i) character 1: lines are not balanced; ii) character 2: buffer size and location; iii) character 8: machine breakdown; iv) character 17: blockage and starvation (downstream stations are idle and upstream stations are blocked); v) character 18: low throughput rate; vi) character 22: long waiting time; vii) character 23: workpiece and movement; viii) character 29: station idle time will increase; ix) character 35: unpaced line; x) character 36: asynchronous; xi) character 37: all workpieces are moved whenever the required operations are completed (workpieces are transferred individually); xii) character 38: buffer installation cost. In the case of an unreliable line, machine breakdown problems will give a significant impact to the production line. This machine breakdown problem leads to blockages and starvation problems among the stations. The nearest upstream station will be blocked because the workpiece cannot be transferred to the next station. Meanwhile, the downstream station will be starved or idle because it cannot receive the workpiece. This leads to high waiting times of workpieces among the downstream stations and total stations' idle times will increase. At this point, the current problem continually evolves to a few more problems in group (vi) such as long lead time and high WIP. In the end, the throughput rate of the production system is low and customer demand might not be achievable. In order to solve this problem effectively, it is worth allocating buffers in the production system. This factor might lead to decision problems regarding buffer size and location. Last but not least, the installation cost of buffers needs to be taken into account because it might have a significant impact on the throughput rate of production.

Based on the evolution of problems stated above, modellers can design solutions for each level of evolution by providing the required elements for performance measures in simulation modelling, starting from less to more complex conditions. Such design changes can help in reducing the complexity of solutions for every level of evolution of problem, based on current requirement and demand. Therefore, evolutionary analysis based on the established cladogram is very useful in helping modellers to design and perform variants of measures for each level of a problems' evolution with simple and relevant elements of templates in simulation modelling.

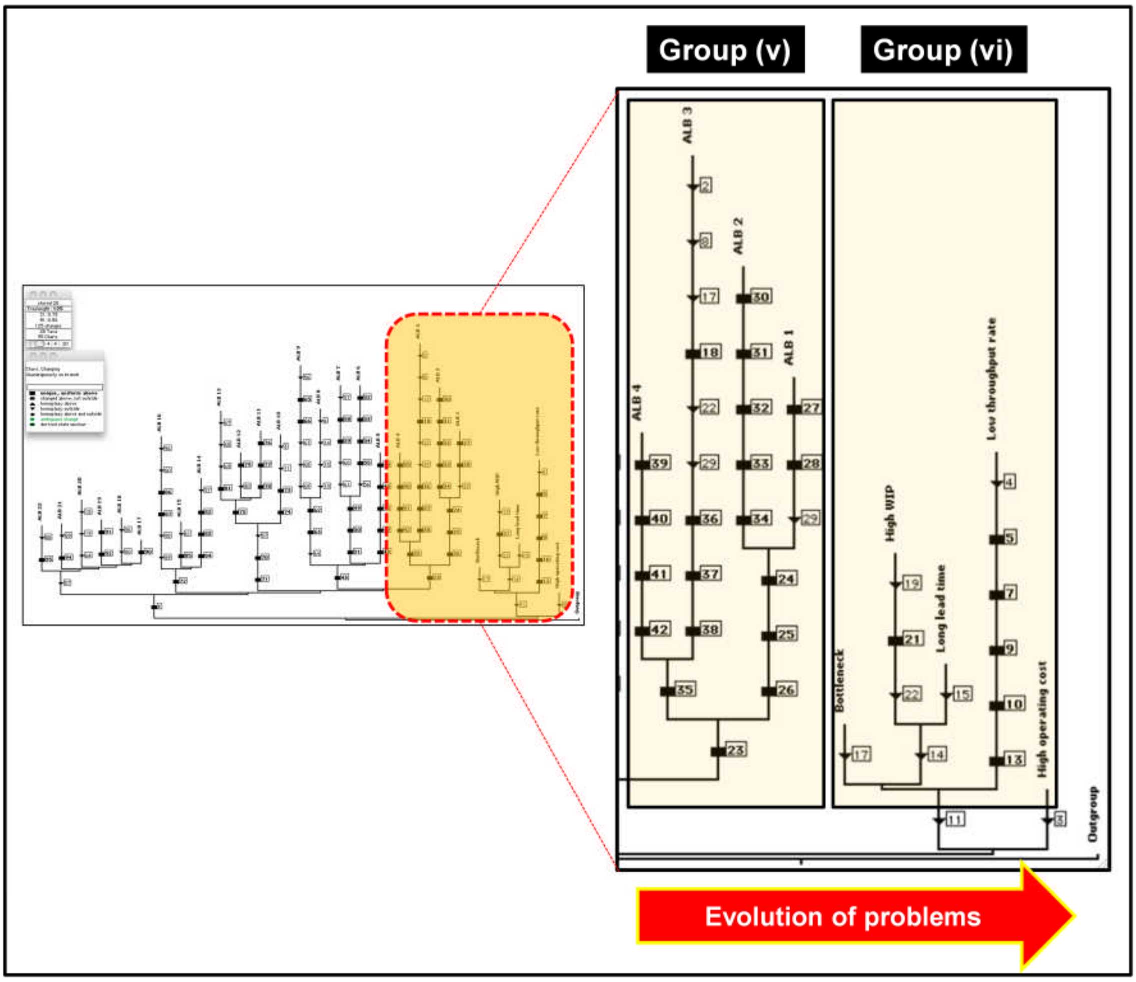

Figure 5-13 Evolution of problems in Group (v) (ALB 3) to Group (vi)

5.7 Chapter summary

A cladogram has been developed for modelling the evolution of problems focusing on assembly lines. It shows the main groups of problems and characteristics involved when the lines are not balanced and how, eventually, these problems evolve into bottleneck problems, high WIP, long lead time, low throughput rate and high operating cost. This evolutionary analysis not only shows the relationships of problems and their evolution but also has useful information, especially in helping modellers to identify the suitable elements that can be used in performance measures in simulation modelling in order to monitor the current problems faced in manufacturing systems. The cladogram and key findings provide a platform for further research in this domain in the future. Biological evolution has been adapted in the context of the manufacturing environment as a new method to reduce time in model building by developing suitable elements for performance measures in simulation modelling in the form of templates. Its practicality has been demonstrated using the cladistics technique to show the evolution of problems, especially in assembly lines.

An established cladogram not only provides useful information in a proper arrangement and structure but its benefits include: i) user can trace the evolution of one problem to another including the characteristics, ii) identifying potential problems in the future; iii) identifying potential solutions and preventive actions for each problem; iv) enhancing solution design decisions so that the problem faced can be tackled effectively through performance measures and simulation modelling; v) determining relevant elements or templates that need to be developed based on established characteristics and problems.

Chapter 6 now shows the development of a proof-of-concept prototype based on the established cladogram which can help users to speed up model building and simulate performance measures in an effective way.

6 DEVELOPMENT OF PROTOTYPE

This chapter focuses on the framework in the development of a prototype, as shown in Figure 3-1 (Stage 3). It discusses all the steps implemented in this research. This chapter is organised into five sections. Section 6.1 focuses on the research methodology and framework for Stage 3 (development of a prototype). Section 6.2 discusses the first phase of the methodology and framework. This section shows the development of templates or elements in detail including templates of physical elements and performance measures. Section 6.3 focuses on the second phase of the research methodology and framework and provides details of the development of a user interface or control panel. Section 6.4 demonstrates the features available, capabilities and step-by-step instructions on how to use the prototype. Section 6.5 provides a summary of the chapter.

6.1 Research methodology and framework

The research methodology for the development of the prototype consists of two phases: i) phase 1: development of the templates (modules); ii) phase 2: development of the user interface (control panel), as shown in Figure 6-1. Both phases are very important in developing the proof-of-concept prototype.

6.2 Phase 1: templates (modules) and development

Phase 1 focuses on how to develop the templates based on the established cladogram. This phase starts by developing a thorough understanding of typical problems in manufacturing systems, especially in assembly lines, as discussed in Chapter 4. The purpose of this activity is to gain information that can be used as sample data in order to establish a classification of problems. The classification is used to find the evolution of problems, especially in assembly lines, as shown in Chapter 5. The classification provides an opportunity to develop a new method that allows simulation models to be generated quickly by providing specific elements in the form of templates based on similarities of problems being tackled and similarities of decisions to be made. The reason behind the hypothesis is that different layouts with the same sets of problems and same decisions to be made could share the same templates (modules).

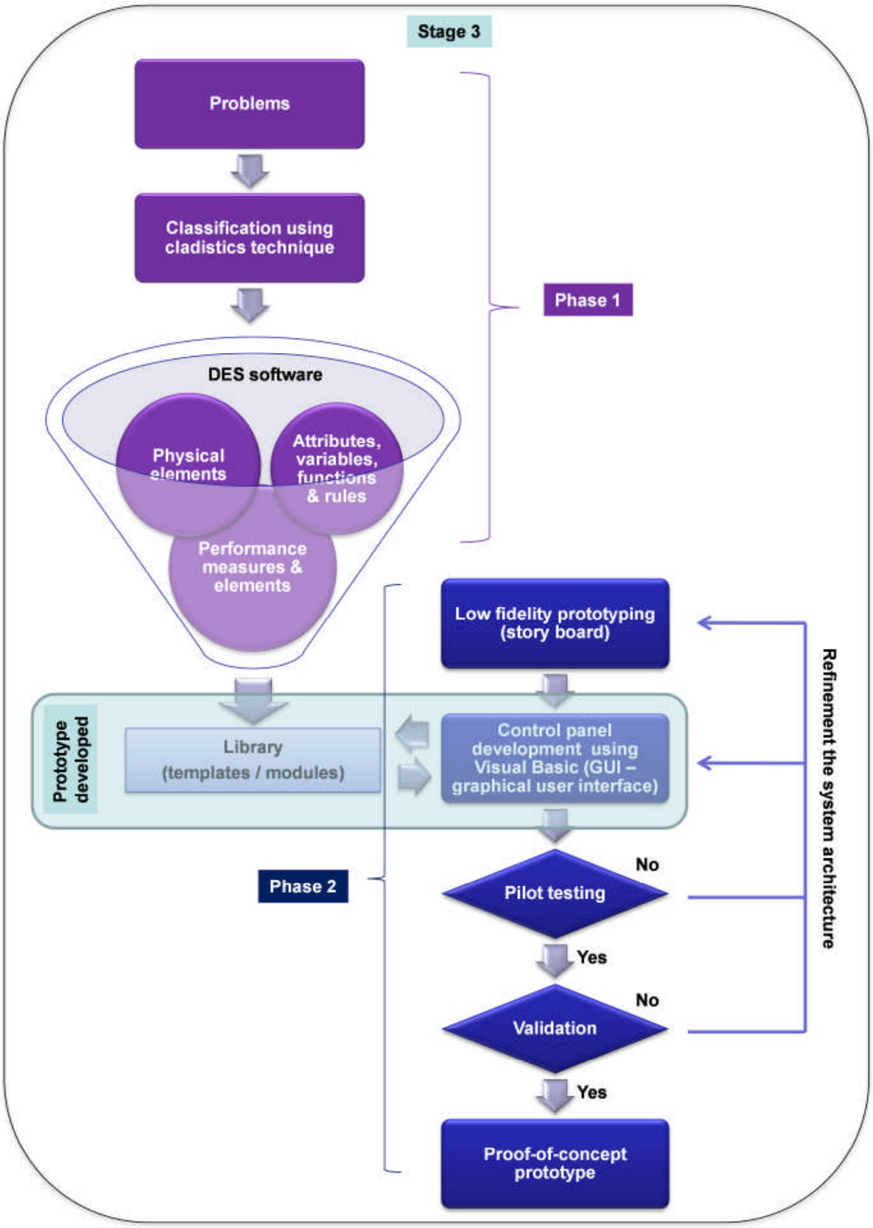

Figure 6-1 Process flow of Stage 3

6.2.1 From cladogram to templates

Classification shows the evolution of problems in assembly lines. A prototype has been developed to demonstrate the proof-of-concept regarding a new method which can rapidly build a simulation model based on classification of problems using the cladistics technique and template approach. Four specific problems have been chosen to prove the concept: i) long lead time; ii) high WIP; iii) bottleneck; iv) high scrap/waste. The number of templates in the library can be increased at any time because they are continuously developed based on the established cladogram. Since Cranfield University has a licence for Witness simulation software, all the templates have been developed using this software. It should be borne in mind that these templates can be developed in any software and the final deliverables may not be using Witness software.

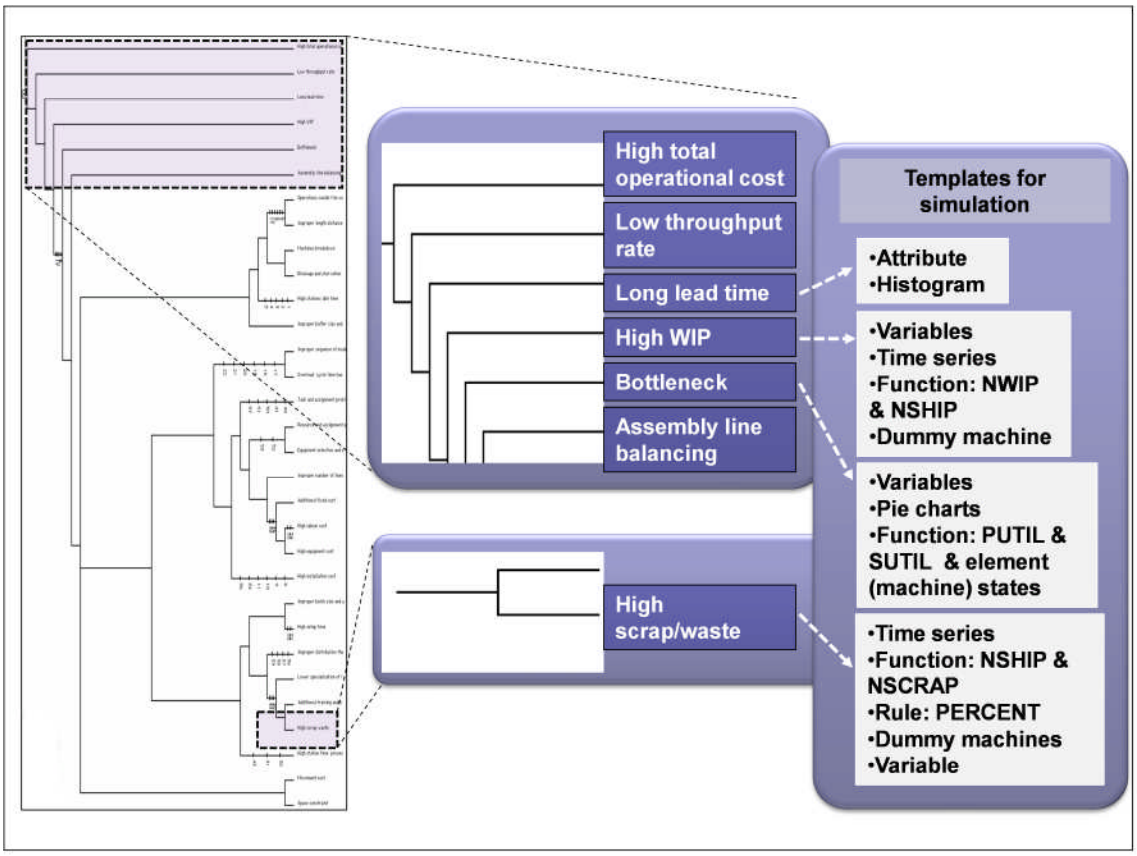

Figure 6-2 Templates development based on the established cladogram

Figure 6-2 shows how the combinations of elements are created as templates (modules), based on the evolution of problems in the established cladogram. Some of the problems with their specific template will be discussed in more detail in the next section.

Long lead time

Figure 6-2 shows that the long lead time problem is caused by many factors, two of which are high WIP and bottleneck problems. In the context of simulation modelling in Witness, lead time can be measured to ensure that the time is not too long and is acceptable. If the lead time is too long it will have a significant impact on the whole production system. Two elements are required in order to measure lead time: i) attribute; ii) histogram. These elements are then created as a template or module which can be retrieved easily from the library developed. The prototype developed provides step-by-step instructions, guiding users on how to build the model and perform the measures using the elements provided. The histogram provided allows the user to graphically present the simulation results of lead time on the Witness screen. Lanner Group (2005) reports that “a histogram is a frequency distribution of values observed for some parameter in the simulation”. One of the advantages of using a histogram is that it keeps track of both the running average and standard deviation. In the context of lead time, the histogram presents the frequency distribution of time between parts entering and leaving the model. An attribute is used to store and calculate the values of time. Those values are then recorded in the histogram using the RECORD statement, as shown in Figure 6-3:

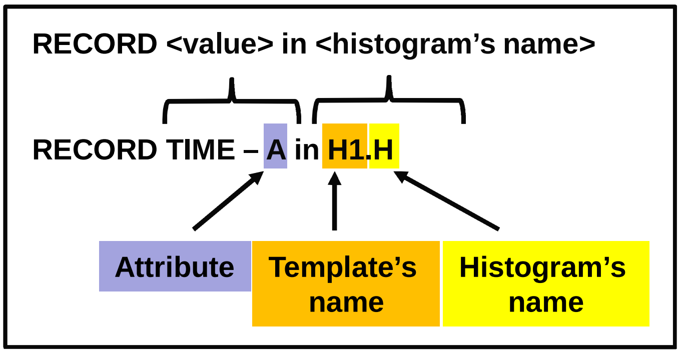

Figure 6-3 RECORD statement for histogram

High WIP

The template or module of WIP consists of three elements: i) time series; ii) variables; iii) dummy machine. A template which consists of these elements is created and stored in the library. The time series element used in the prototype plots the number of parts in progress in the model and number of throughput or parts shipped from that model. The Lanner Group (2005) describes how “at specified intervals a ‘reading’ is taken from the model and ‘plotted’ on a graph. As time passes, a series of values will be plotted from left to right in the graph. Once the space on the screen allocated to the time series has been exhausted, the graph ‘scrolls’ to allow the new plots to be made. Time series are useful for determining the trends or cycles underlying the models, since they provide a ‘history’ of the specified value”. NWIP and NSHIP functions have been employed to calculate and return the values to the time series as shown in Figure 6-4. These values will be graphically plotted over time on the Witness screen. The data types used in the general expression: i) (R); ii) (N); are briefly explained in Appendix A.

In the other aspects of development, it is shown that one template can be linked to the other templates. The template for WIP is linked to the template for parts in order to graphically present the simulation results on the Witness screen. It shows that the scope and level of complexity of one simple template can be expanded by linking it to other templates in order to cope with more complicated scenarios.

General expression:

NWIP $^{(R)}$ (part $^{(N)}$)
NSHIP $^{(R)}$ (part $^{(N)}$)

	Expression
Number of parts currently in progress	**NWIP (Part1.p1)**
Number of parts that have been shipped	**NSHIP (Part1.p1)**

Template's name **Part's name**

Figure 6-4 Plot expression for NWIP and NSHIP functions in time series

<u>Bottleneck</u>

The template or module of the bottleneck consists of three elements: i) pie charts; ii) variables; iii) PUTIL and SUTIL functions apply to the breakdown of a machine. In the context of this research, the main function of pie charts is to show the percentage utilisation of a breakdown machine. Lanner Group (2005) report that the "PUTIL function returns the percentage utilisation of an element in a particular state and SUTIL function returns the percentage on-shift utilisation of an element in a particular state. If an index of 0 is specified, it returns the average of all these elements. The code numbers to use for each state appear under ISTATE. PUTIL and SUTIL functions apply to machines, conveyors, tracks, vehicles, labour, processors, pipes, tanks, networks, carriers, sections and stations". In the prototype development, these functions have been applied to a breakdown of a machine. The expressions for the functions and machine states used are shown in Figure 6-5. The data type used in the general expression: i) (R); ii) (N); iii) (I); iv) machine states, are briefly explained in Appendices A and B.

General expression:

PUTIL $^{(R)}$ (element $^{(N)}$, state $^{(I)}$)
SUTIL $^{(R)}$ (element $^{(N)}$, state $^{(I)}$)

Percentage (%)	Expression
Machine utilisation	**PUTIL (SM6.SM,2)**
Idle time (waiting for parts)	**PUTIL (SM6.SM,1)**
Broken down (being repaired)	**PUTIL (SM6.SM,5)**

Template's name

Machine's name

Machine's states

Figure 6-5 General expression for PUTIL and SUTIL functions

High scrap/waste

The high scrap/waste template or module is comprised of a three elements: i) time series; ii) dummy machines; iii) variables. NSHIP and NSCRAP functions have been used to return the number of parts that have been shipped and scrapped. The time series element allows the users to graphically present these values on the Witness screen. A PERCENT rule is used to send the part or entities to several elements on a random percentage basis, as shown in Figure 6-6. Based on that figure, 90% of parts will be sent to a dummy machine which is called “DMShip” and 10% of parts will be sent to another dummy machine which is called “DMScrapped”. In addition, variables are used to display the number of parts that have been shipped and scrapped in the dummy machines.

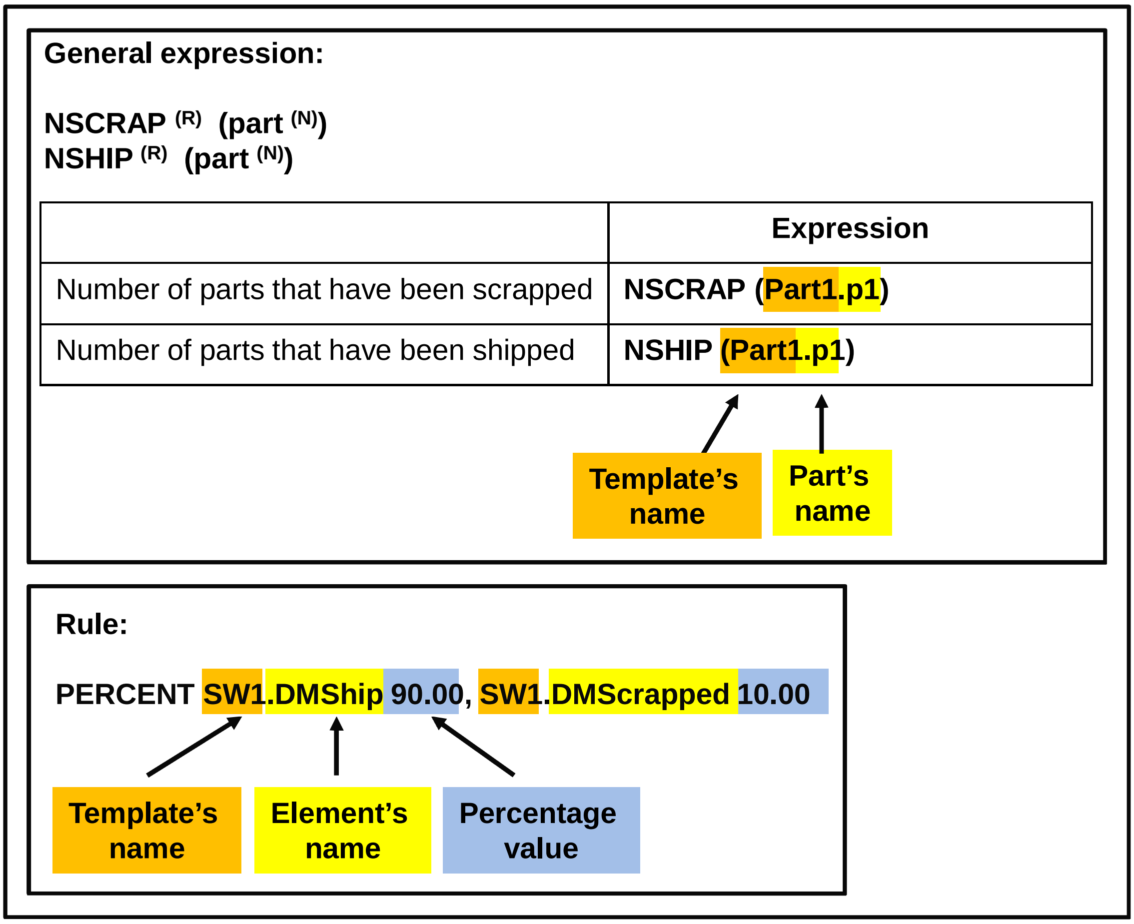

Figure 6-6 General expression and rule for scrap/waste template

6.2.2 Physical elements and templates

This research project is comprised of two layers: i) First layer: physical elements and layout; ii) Second layer: problems and performance measures. The first layer is very important in developing the model which consists of physical elements. Then the second layer provides all the elements required for performance measures in order to monitor the established problems. Both layers are very important in facilitating users in model building and reducing model development time.

The prototype developed will facilitate users by preparing the physical elements for model development and also providing the elements for performance measures. Some of the physical elements have been selected for templates or modules development. Those templates consist of a single element or combination of elements: i) machine; ii) buffer; iii) conveyor; iv) part; v) buffer, machine and conveyor; vi) buffer, machine and labour.

At the present moment, the developed prototype is capable of accommodating up to 99 templates or modules but this quantity can be increased based on the requirement. All templates or modules are stored in a library in .mdl format and all of them are continuously developed based on the established cladogram. Therefore, all templates can be changed, added or deleted, based on users' requirements.

6.3 Phase 2: user interface (control panel)

Phase 2 focuses on the development of the prototype. The prototype has two main features: i) library of templates (modules) as discussed in the previous section; ii) user interface (control panel): engine of the prototype. This section will give more focus on how to develop this engine or control panel. This secondary user interface or control panel is very important in providing two ways of interaction or links between user and Witness software. As we know, simulation software does not have the "ease-of-use" expected and it takes time to develop understanding and skills. Therefore the proof-of-concept prototype facilitates users not only in using the Witness software but also in developing the simulation model. Phase 2 consists of four stages of development: i) low fidelity prototyping; ii) development of control panel; iii) pilot testing; iv) testing and validation. Pilot testing and validation results will be presented in Chapter 7.

6.3.1 Low fidelity prototyping

Low fidelity prototyping is used to view and depict concepts, design and layouts of the user interface (control panel). It is intended to establish the general look of the control panel and put in the picture some simple information about how the control panel operates.

The control panel has been designed to provide three different scenarios as shown in Figure 6-7: i) normal simulation modelling; ii) changing the routing (featured by ON/OFF switch for templates or elements); iii) performance measures. The prototype will help the user by providing the physical elements, running the model, changing the route and doing the performance measures.

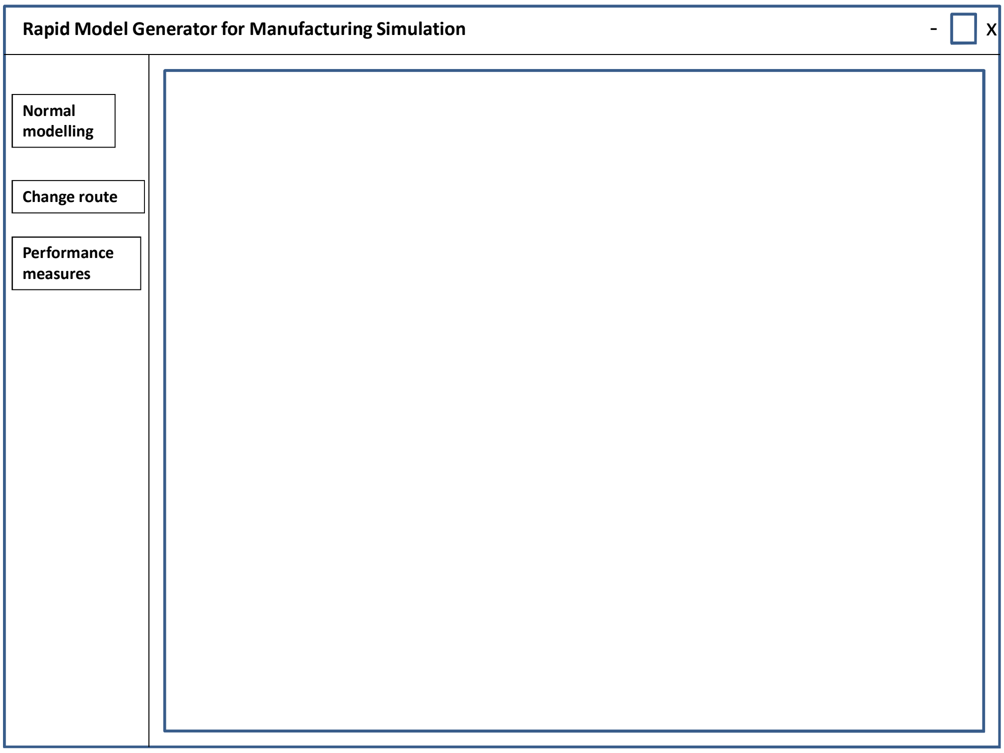

Figure 6-7 Front page of the control panel

Normal simulation modelling

In this scenario, the prototype will help the user to create the physical elements, make a route for the part and run the model. Firstly, the user is required to choose the layout but only the assembly line layout is available at the moment, as shown in Figure 6-8. Secondly, the user is required to select the physical elements and their quantity, as shown in Figure 6-9. These physical elements have been developed in the form of templates or modules. All these elements will be generated automatically on the Witness screen based on the user input in the control panel.

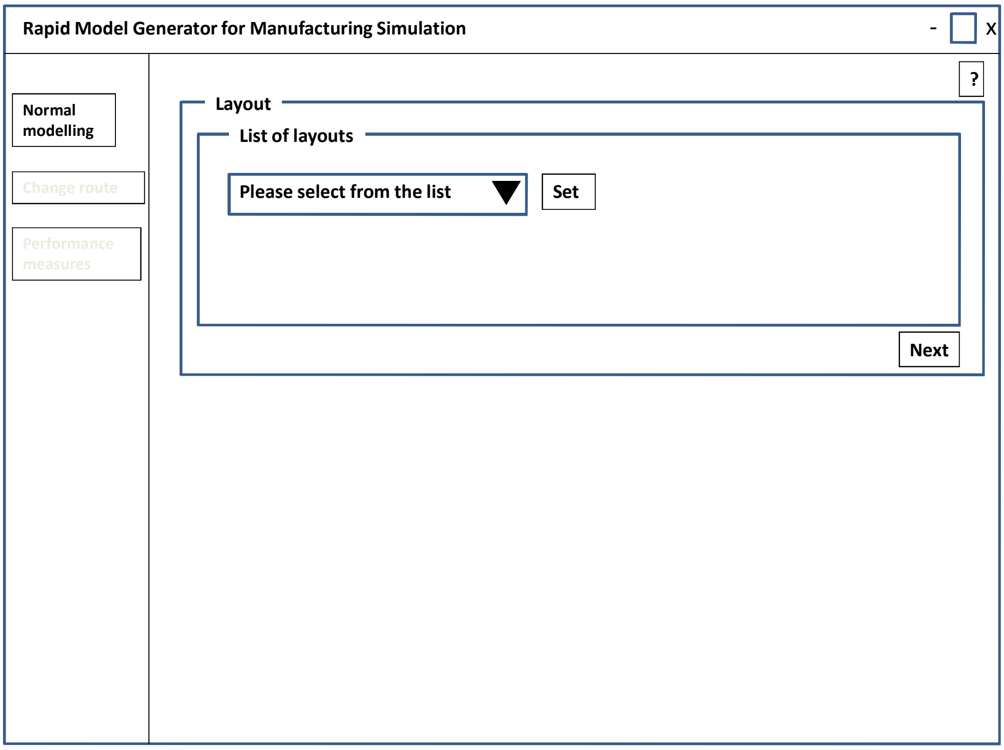

Figure 6-8 List of layouts

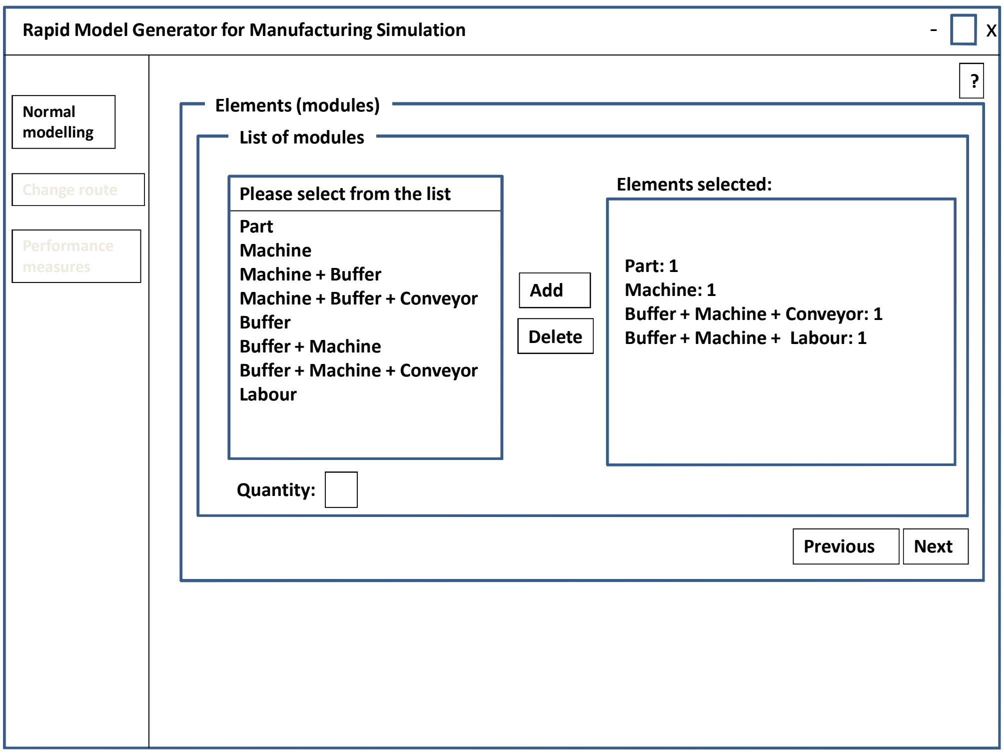

Figure 6-9 List of templates (modules) and quantity

Figure 6-10 shows the third section in the normal simulation modelling after the user has selected the required elements. This section provides the routing summary for the part and can be changed at any time. The list of destinations will be sent to Witness software automatically based on user input in the control panel developed.

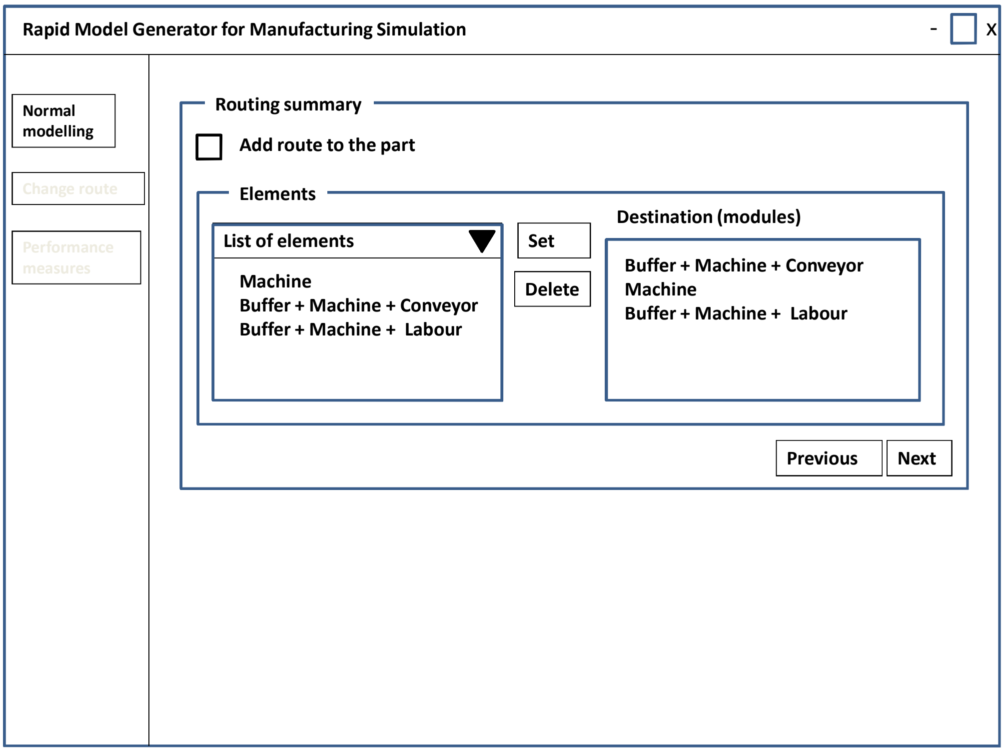

Figure 6-10 Routing for the part

Changing the routing

This second scenario provides one more interactive feature whereby the user can take a control of the selected routing summary for the part. This feature allows the user to change the current routing summary by switching the ON (active) or OFF (inactive) of any elements in the templates (modules), as shown in Figure 6-11. Switching OFF means that the part will bypass selected elements based on user input in the control panel. Therefore users do not have to delete the unwanted elements in any templates because they only need to switch OFF those elements. Apart from that, the user can gain access to the previous scenario in case the current route needs to be changed.

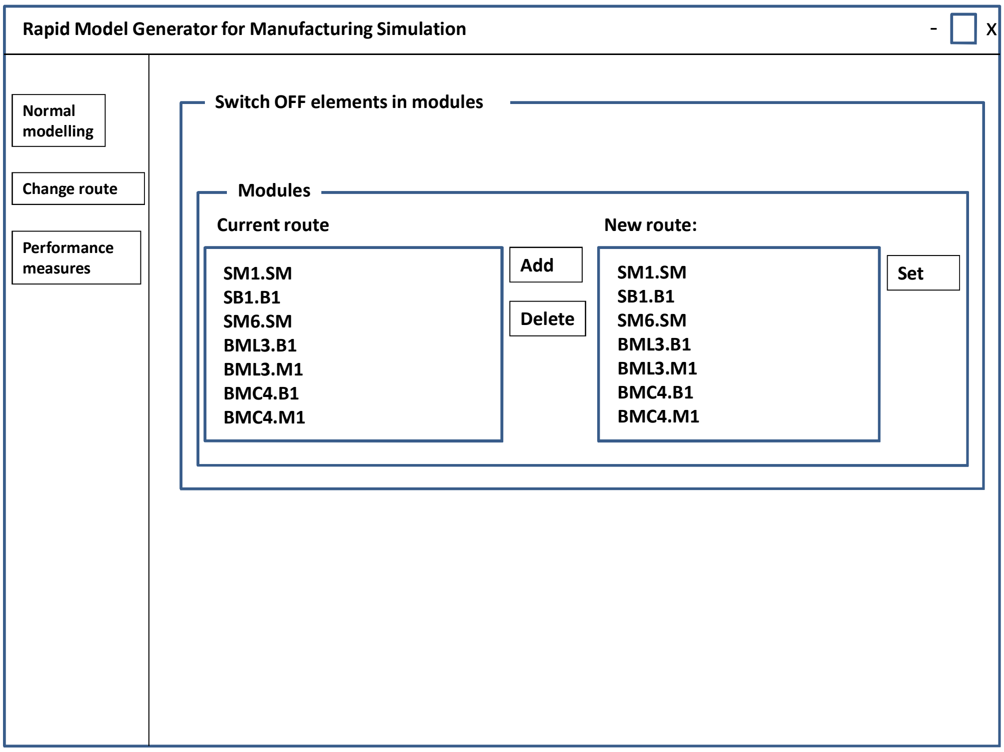

Figure 6-11 Switching ON/OFF elements

Performance measures

The third scenario allows the user to do performance measures on the developed model, as shown in Figure 6-12. Each problem, including its specific elements, is created as a template. The user can, therefore, select the relevant problems to be measured and the prototype will provide the elements required to do the measures on the Witness screen. Apart from that, the prototype also provides instructions or step-by-step guidelines to the user to carry out the performance measures easily.

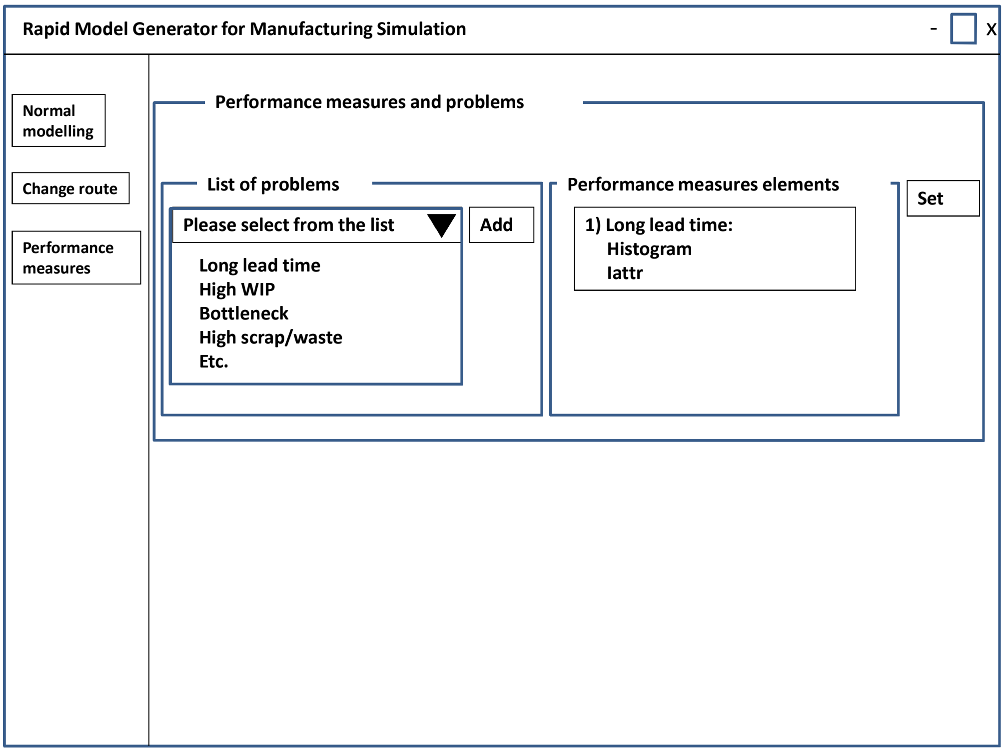

Figure 6-12 Performance measures and elements

6.3.2 Graphical user interface and development

The prototype developed consists of three main components: i) library; ii) user interface (control panel); iii) Witness screen. The main function of the prototype is to facilitate the user in model building, especially in the Witness environment. The control panel developed can be assumed to be the engine of the prototype. It is linked to the library and Witness software. This control panel receives the user inputs, processes them and displays the output on the Witness screen, as shown in Figure 6-13. The control panel provides two ways of interaction between the library and Witness environment. The library is used to store all the templates in the .mdl format. The templates represent the physical elements and performance measure elements that have been developed using Witness software.

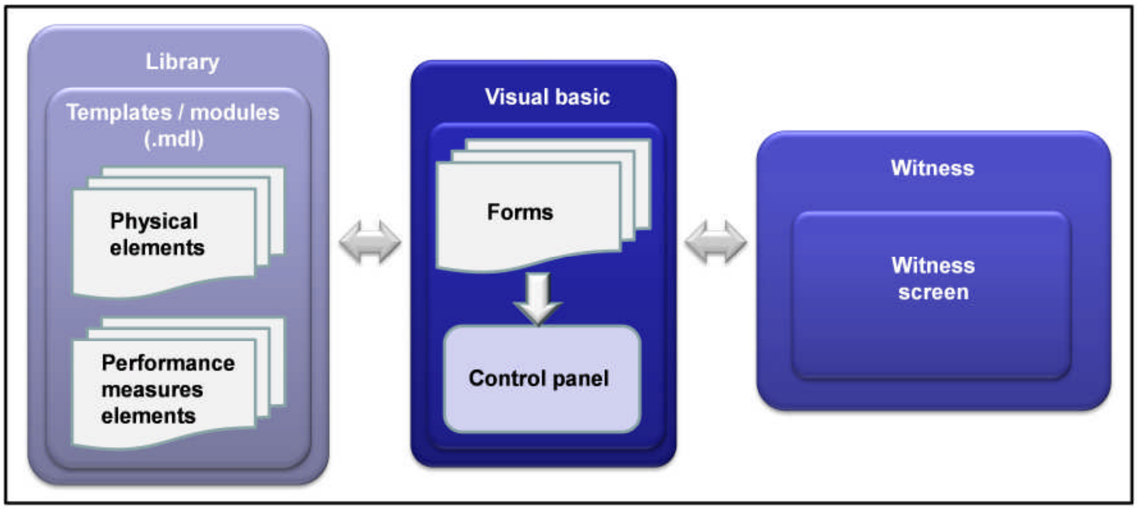

Figure 6-13 Framework of prototype developed

6.3.3 Interfacing Visual Basic and Witness

<u>**Visual Basic**</u>

The functions of Visual Basic programming language in this research can be divided into two categories: i) to develop the user interface (control panel); ii) as a processor or engine of the prototype through the control panel developed. User input from the control panel will be processed here and will return the output to the Witness software for simulation modelling purposes. The control panel consists of a few forms which are linked to each other. Global variables and local variables have been used to send data from one form to the other forms, as shown in Figure 6-14. Buttons are used to send data between the forms and to shift from one form to the others.

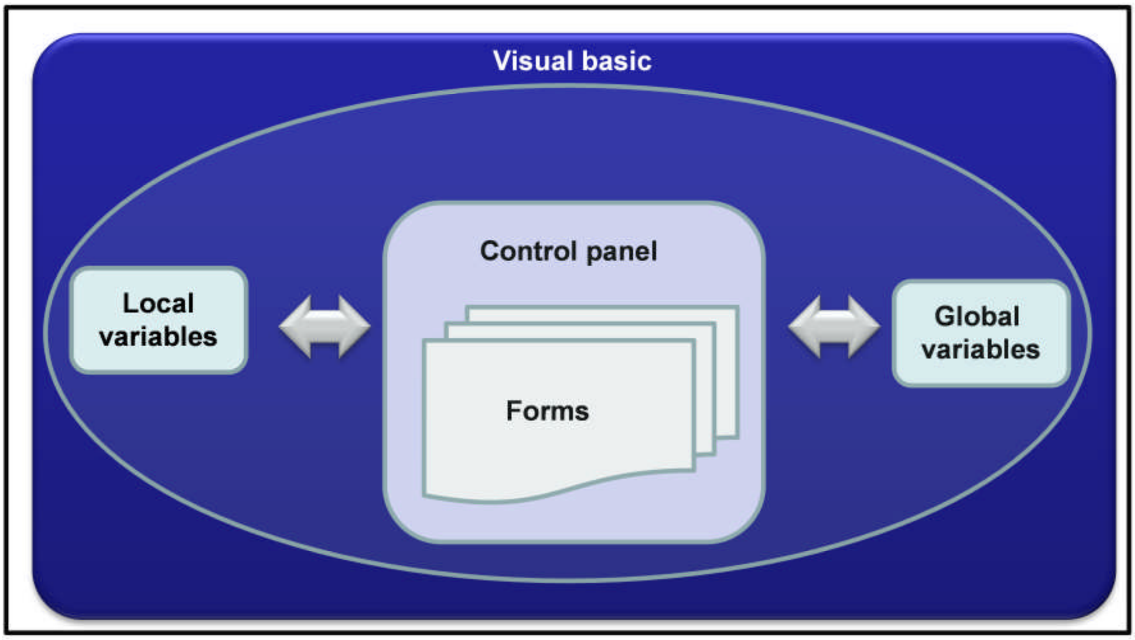

Figure 6-14 Control panel development in Visual Basic

Global variables, local variables and arrays are very important in the development of the prototype. Those variables and arrays are used to store dynamic changes of data between the control panel and Witness, based on user input. The dynamic changes of data are required in a few situations such as the list of destinations for routing functions in Witness.

List of destinations and routing functions

There are few methods that describe the flow of parts through the model in Witness, such as routing function and input/output rules using the pull/push function. The prototype is expected to provide the routing summary of parts automatically and dynamically in order to facilitate model building and to reduce the model development time. Since the author could not gain access to the element's properties in Witness from Visual Basic, the pull/push function could not be implemented in the development of the prototype. Therefore, the author has investigated a new approach by enhancing the current routing function available in Witness, as shown in Figure 6-15. This approach is capable of producing a dynamic list of destinations for the routing summary in Witness because the list can be changed and regenerated automatically from Visual Basic.

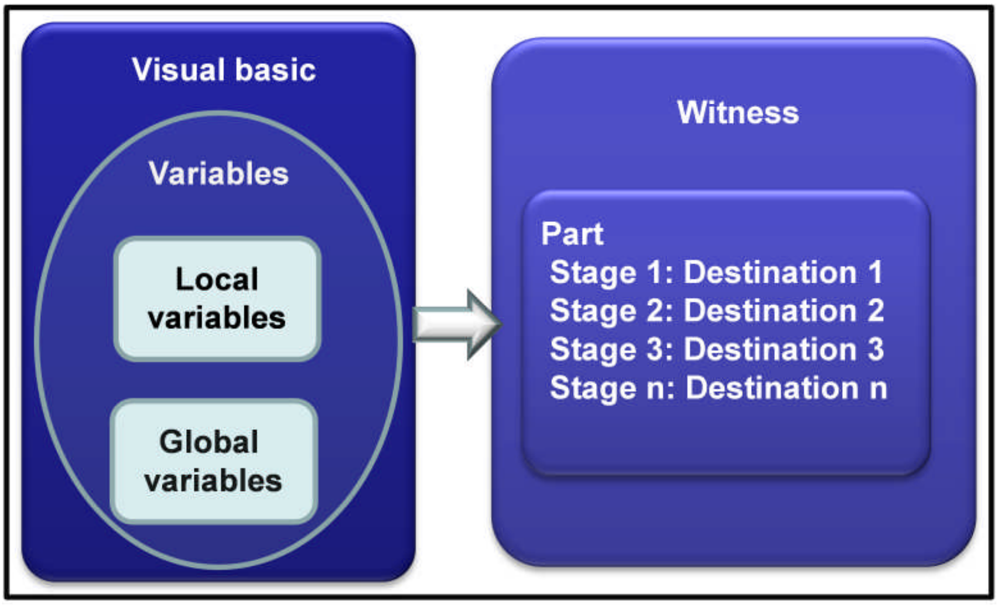

Figure 6-15 Dynamic list of destinations

Witness

The main function of Witness is to provide facilities in model building and simulation. In the context of this research, Witness is used to develop templates or modules. Based on the user input from the control panel, Witness provides the required templates and displays them on the Witness screen. Load module function has been used to retrieve the templates or modules from the library. Specific codes have been developed in Witness to calculate the two-dimensional (2D) coordinates dynamically. These coordinates are used by the load module function to position all the templates (modules) requested by the user from the control panel to the Witness screen automatically, as shown in Figure 6-16. Identical templates are positioned vertically in a group. Each group of templates is positioned horizontally. These vertical and horizontal positions are generated dynamically and automatically based on the calculation of 2D coordinates programmed in Witness.

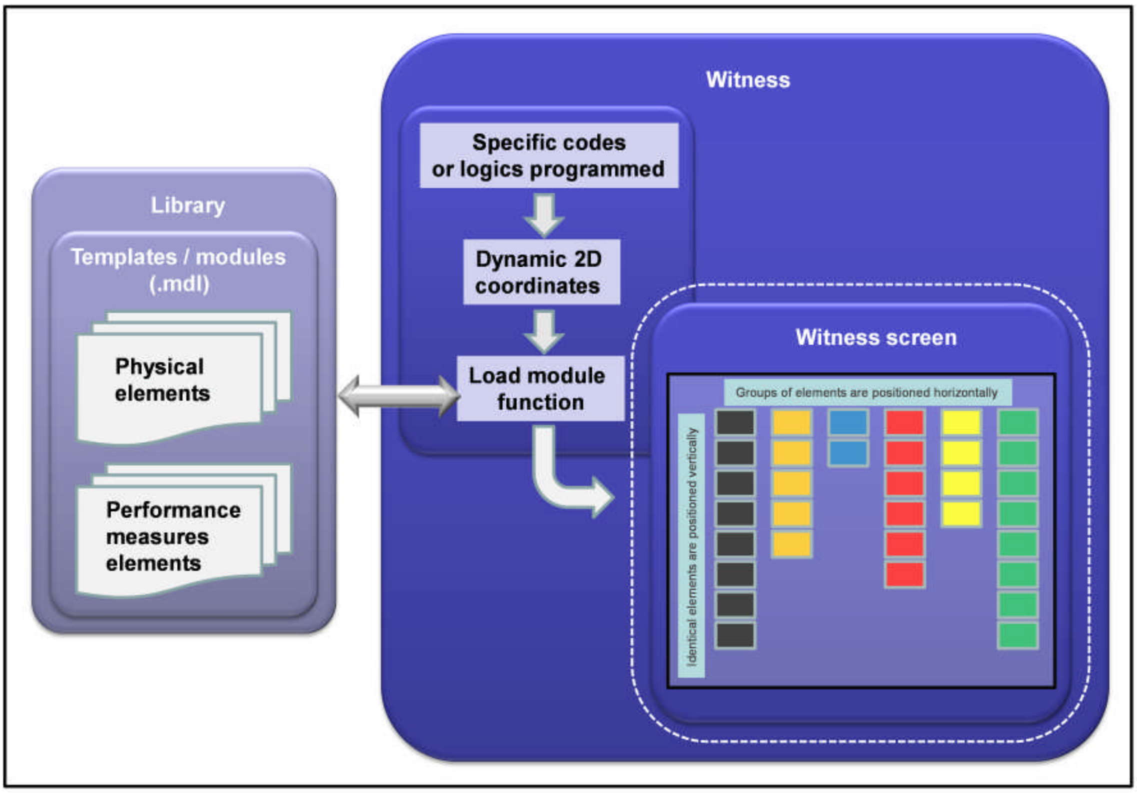

Figure 6-16 2D coordinates and default position of templates

6.4 Proof-of-concept prototype

The control panel of the prototype has been designed based on three scenarios: i) normal simulation modelling; ii) changing the routing (featured by the ON/OFF switch for templates or elements); iii) performance measures. The scenarios provided will help the user in developing both the physical elements of the model and the routing summary of the part, and providing specific elements for performance measures.

The control panel consists of three main sections: i) Scenarios (left); ii) Sections of user interface that will be changed automatically based on scenarios (in the middle); iii) Controller (right), as shown in Figure 6-17. Three main scenarios are provided in the first section: normal modelling, changing the routing and performance measures. In the normal modelling scenario, this prototype will facilitate the user in developing a model by providing the templates of physical elements, making a route for the part or linking the elements (templates) and running the model. In changing the routing scenario, the prototype will facilitate the user in making changes on the established routing and providing one unique feature which allows the user to switch ON/OFF any elements in templates and then linking those elements automatically as a new route. In performance measures scenarios, the prototype will facilitate the user in performing the measures on some established problems. The prototype provides the guidelines and specific elements required for the user to perform the performance measures easily and faster.

The second section which is located in the middle of the control panel consists of a few forms that will be changed automatically based on the scenario established. This section is very important in the development of the prototype because it will receive all the inputs from the user before the prototype processes the data and sends the output to the Witness software.

The third section of the control panel which is located on the right is called the controller and is comprised of four buttons:

- Begin: to set the values that have been processed and calculated to variables programmed in Visual Basic before sending them to Witness software
- Run: to run the model from the control panel
- Stop: to stop the simulation process from the control panel
- Help: to provide the guidelines on how to use the prototype

Generally, there are three main functions of the controller: i) to send data which has been processed in Visual Basic to Witness software; ii) to control (initialise, run and stop) the process of simulation of the model using the control panel; iii) to provide instructions or guidelines on how to use the prototype.

Figure 6-18 shows some windows that have been customised in the Witness environment for the development of the prototype. Apart from the default window for the physical elements, additional windows have been developed for the user: i) a window that shows the instructions and logics required for the user to carry out the performance measures; ii) a window that shows the elements for the performance measures, such as histogram, time series and pie charts; iii) a window that shows the legend and keys for the selected elements' states, such as machine and buffer.

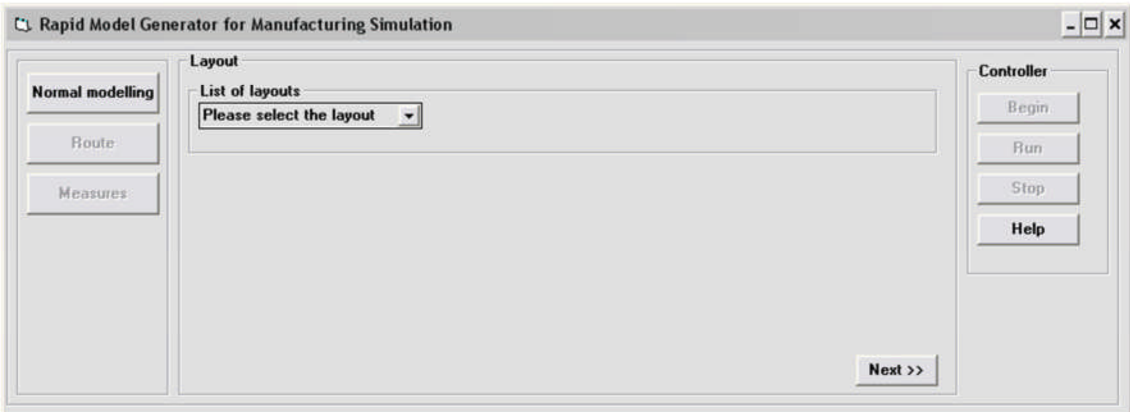

Figure 6-17 Control panel and its sections

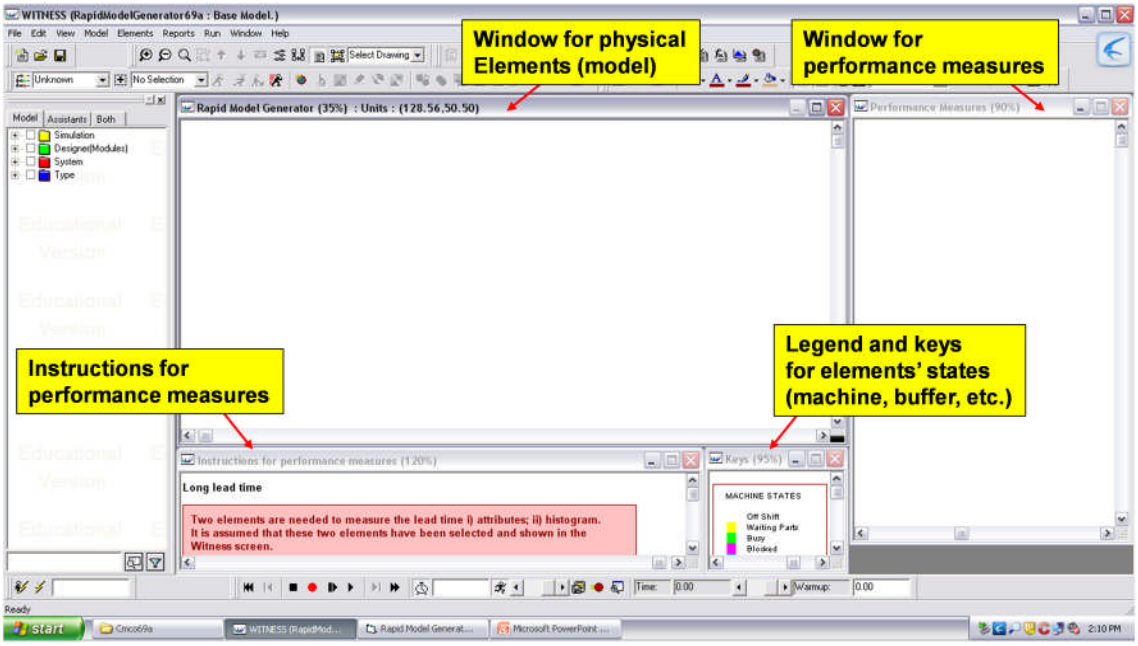

Figure 6-18 Witness screen and its customised windows in prototype

6.4.1 Normal simulation modelling

In the normal simulation modelling scenario, the user is required to choose the “Assembly line” from the list of layouts, as shown in Figure 6-19 (number 2). By clicking the “Next” button, the control panel will show the next page. Apart from that, the control panel provides guidelines for the user on how to use the developed prototype, as shown in Figure 6-19 (number 1).

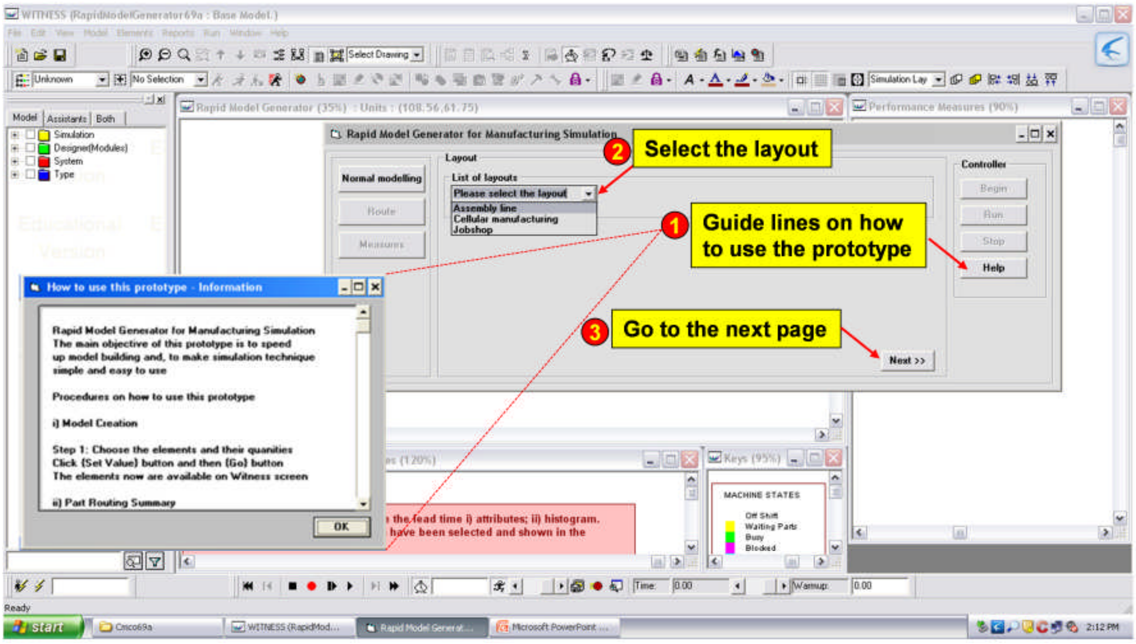

Figure 6-19 First page of control panel

In the next page, the user is required to select the physical elements based on templates or modules provided (number 1) and specify the quantity of each template (number 2), as shown in Figure 6-20. The control panel then processes the user input and assigns the output to the appropriate variables when the user clicks the “Begin” button. The “Run” button is used to send the values of the variables to the Witness environment and displays the templates of physical elements required on the screen, as shown in Figure 6-21. After the physical elements have been selected, the user is required to position each element (template) based on the layout provided, as shown in Figure 6-22. The positions of templates can be changed (drag and drop) at any time based on requirements.

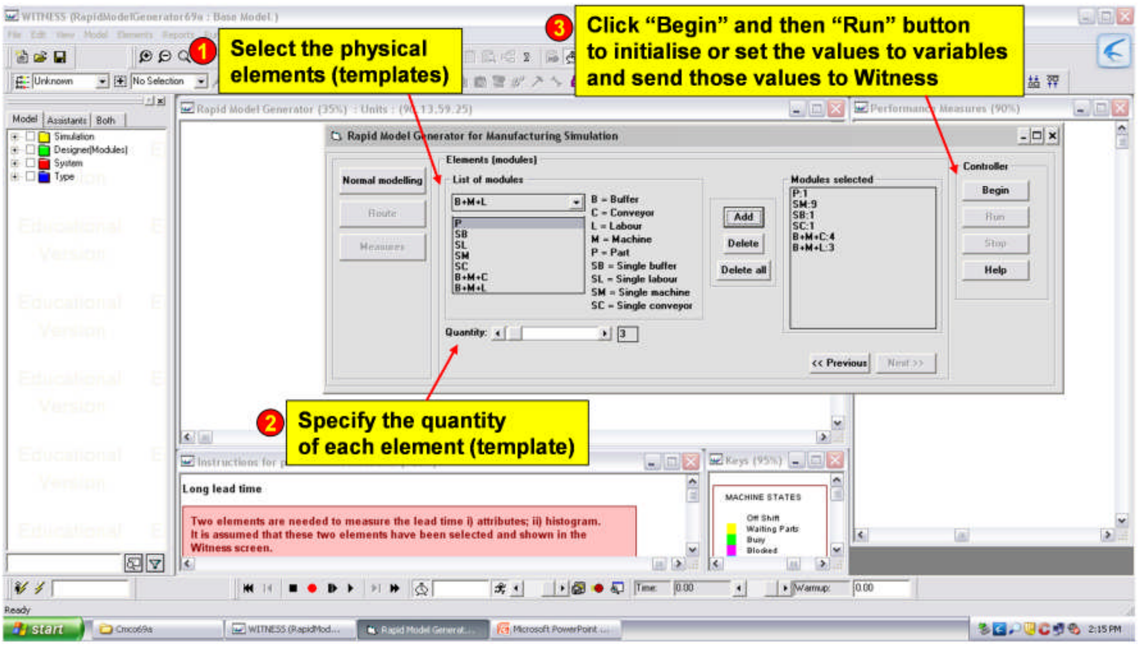

Figure 6-20 Selection of templates and quantities

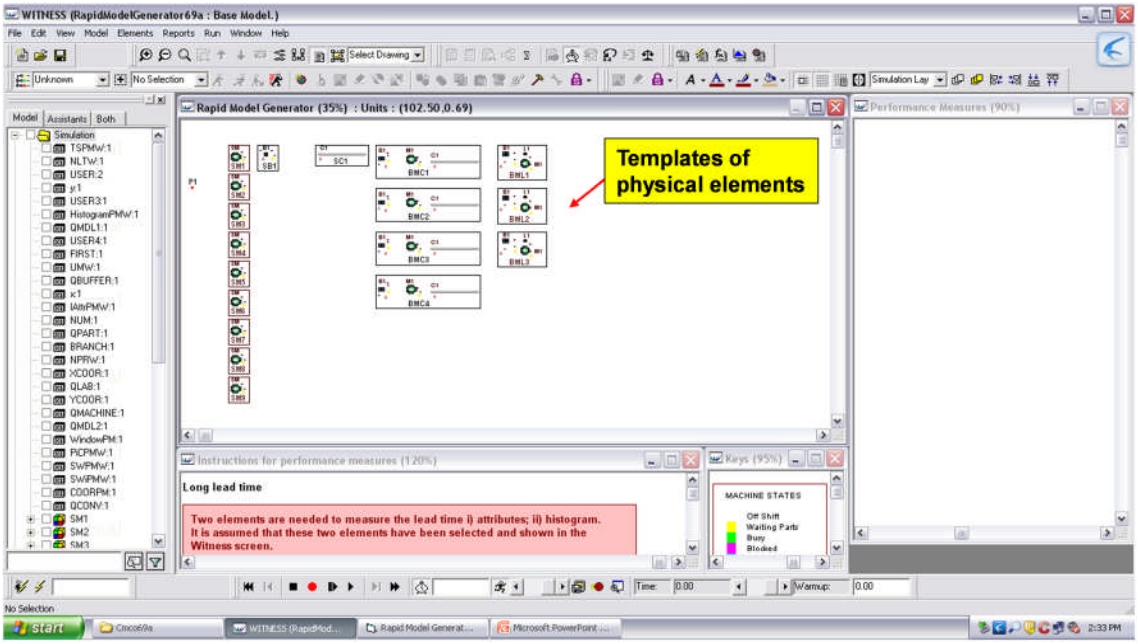

Figure 6-21 Templates of established physical elements

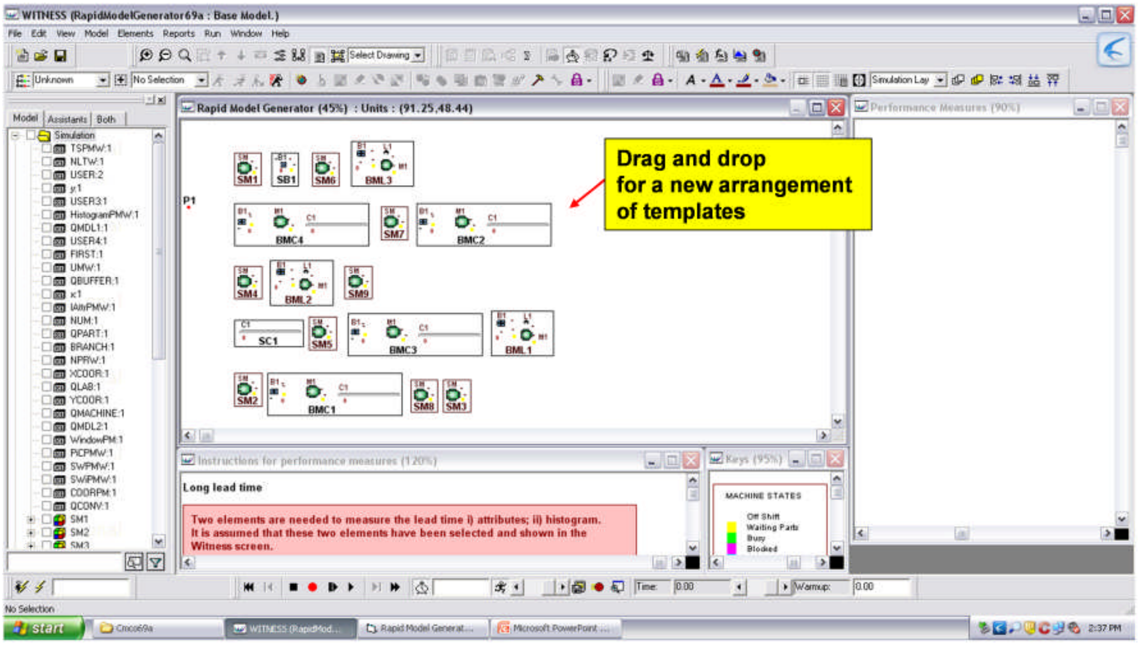

Figure 6-22 Rearrangement of templates (modules)

In the next page, the user is required to make a route for the model, as shown in Figure 6-23. A list of templates (number 2) is automatically generated, based on templates selected by the user, as shown on the Witness screen. A list of destinations selected by the user is shown on the right of the control panel (number 3). If there are any changes to the selected destinations, the user can delete any elements or the whole list by using the “Delete” or “Delete all” button. The user needs to click the “Begin” button (number 4) so that the control panel will process and initialise the appropriate variables to Witness. Next, the user can run the model using the “Run” button provided. To stop the simulation process, the user needs to click the “Stop” button and a window (number 5) will automatically appear to help the user with the next actions or steps. One of the advantages of this prototype is that the user can change the route established at any time and the prototype will make the changes or generate a new route in real time.

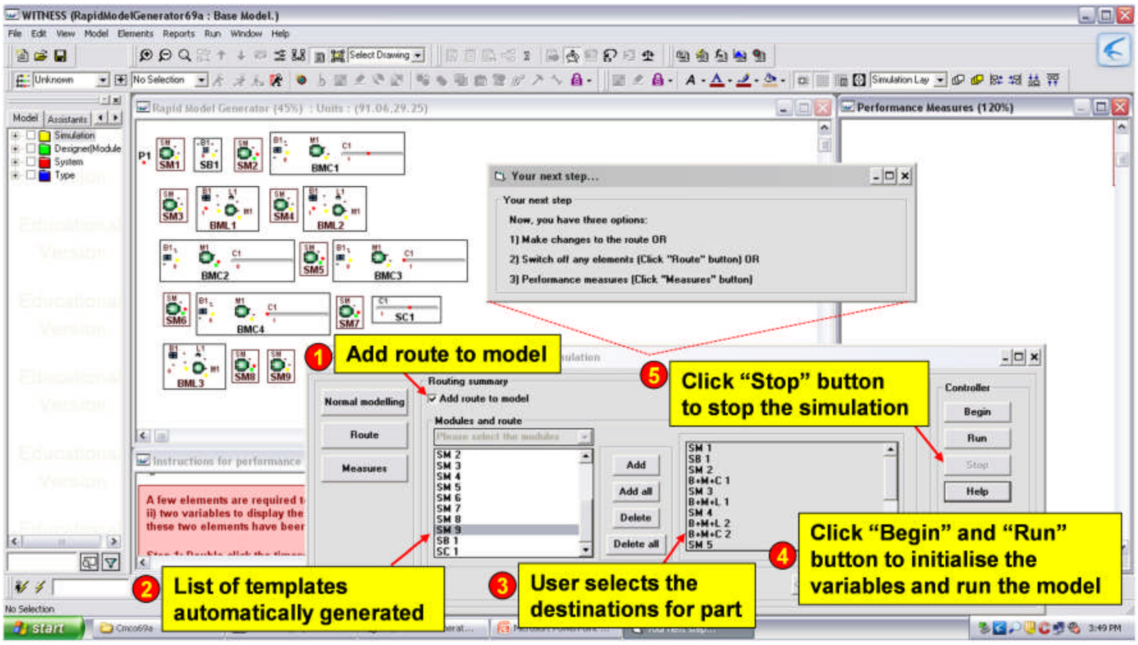

Figure 6-23 Routing summary for the model

6.4.2 Changing the routing

In changing the routing scenario, the user is required to make some changes to the current route so that the part will bypass the circled elements, as shown in Figure 6-24. The user needs to click the "Route" button to display this page. A list of elements for each template (number 1) will be automatically generated by the prototype, based on the routing summary selected by the user from the previous page. When the user clicks the "Add all" button, the list of established elements (number 1) will be copied to the new route list (number 2). The user is required to specify the elements that need to be switched OFF by using the "Delete" button. Then, the user needs to click the "Begin" and "Run" button (number 3) in order to regenerate a new routing summary and run the simulation process for the model. To stop the simulation process, the user needs to click the "Stop" button and a window (number 4) will automatically appear to help the user with the next actions or steps.

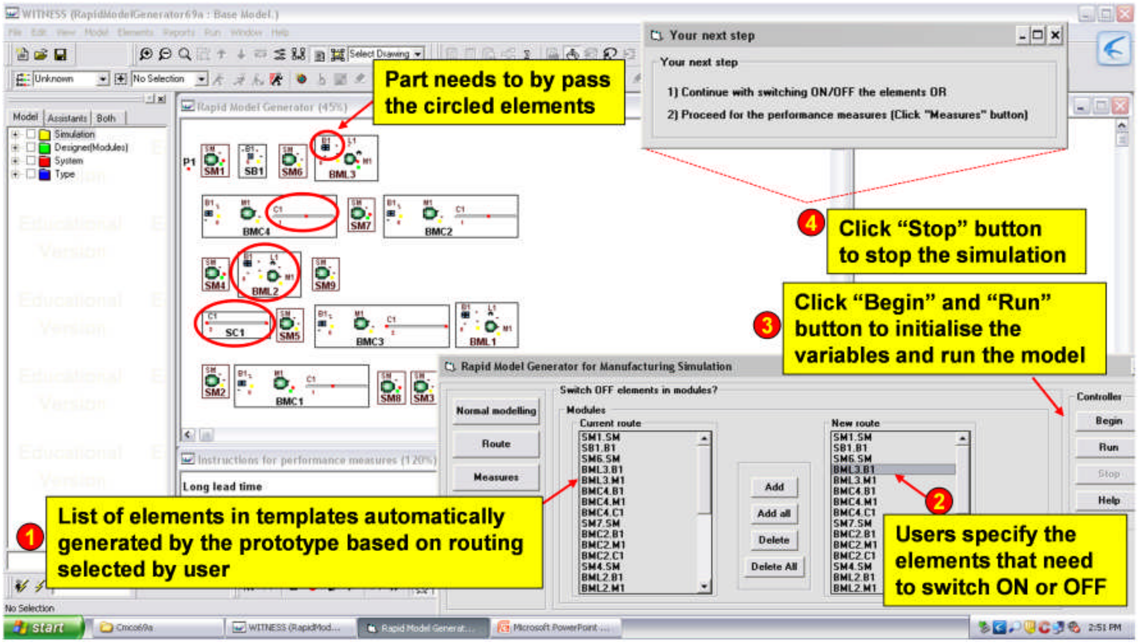

Figure 6-24 Regenerating a new route by switching ON/OFF some elements (templates)

6.4.3 Performance measures

In the performance measures scenario, the user is required to measure the effects of machine reliability (breakdown) against lead time, WIP and machine utilisation based on four conditions: i) machine breakdown at the beginning of the line; ii) machine breakdown towards the end of the line; iii) machine breakdown is frequent (short MTBF) but the repair time is quick (short MTTF); iv) machine breakdown is infrequent (long MTBF) and the repair time is long (long MTTF). The user needs to select the problem from the list (number 1) and the specific elements required to carry out the performance measures will be displayed (number 2), as shown in Figure 6-25. Then, the user needs to click the “Begin” and “Run” button (number 3) so that the control panel can process and assign the values to the appropriate variables before sending them to Witness.

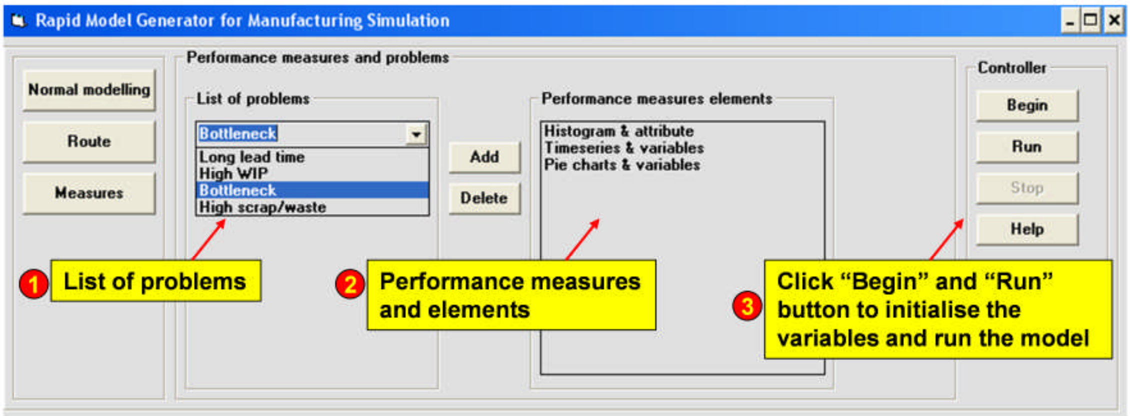

Figure 6-25 Control panel and performance measures

<u>Conditions 1 and 2: To measure the effects of machine breakdown at the beginning and towards the end of the line against lead time, WIP and machine utilisation</u>

Figure 6-26 and Figure 6-27 show the effects of machine breakdown at the beginning and towards the end of the line against lead time, WIP and machine utilisation. Based on the results, the user can make a comparison for both situations and plan for the next actions which will benefit the production line. The developed prototype provides all the elements (templates) required for the performance measures in Witness (number 1). Since the user is required to type in some logics in order to carry out the performance measures, the instructions and guidelines are provided (number 2), as shown in those figures. The prototype allows the user to graphically present the simulation results on the specific elements provided in real time. The prototype has been designed and developed with some features which are not only useful in rapidly building the physical elements of the model and routing summary, but are capable of providing specific elements and guidelines for performance measures.

Apart from that, the prototype provides useful information regarding the evolution of problems based on the elements provided. It can be clearly seen that machine breakdown will be a bottleneck to the whole line. The bottleneck machines affect the amount of WIP in the system and this situation will have a significant impact on the lead time. The prototype that has been developed is capable of facilitating the user to carry out effective measures in order to monitor those related problems. Those elements or templates will graphically present the simulation results in real time. The user can freely make any changes or modifications to the model, including the elements (templates) provided, and observe the results in real time. This kind of approach will provide a very interactive way of simulation modelling.

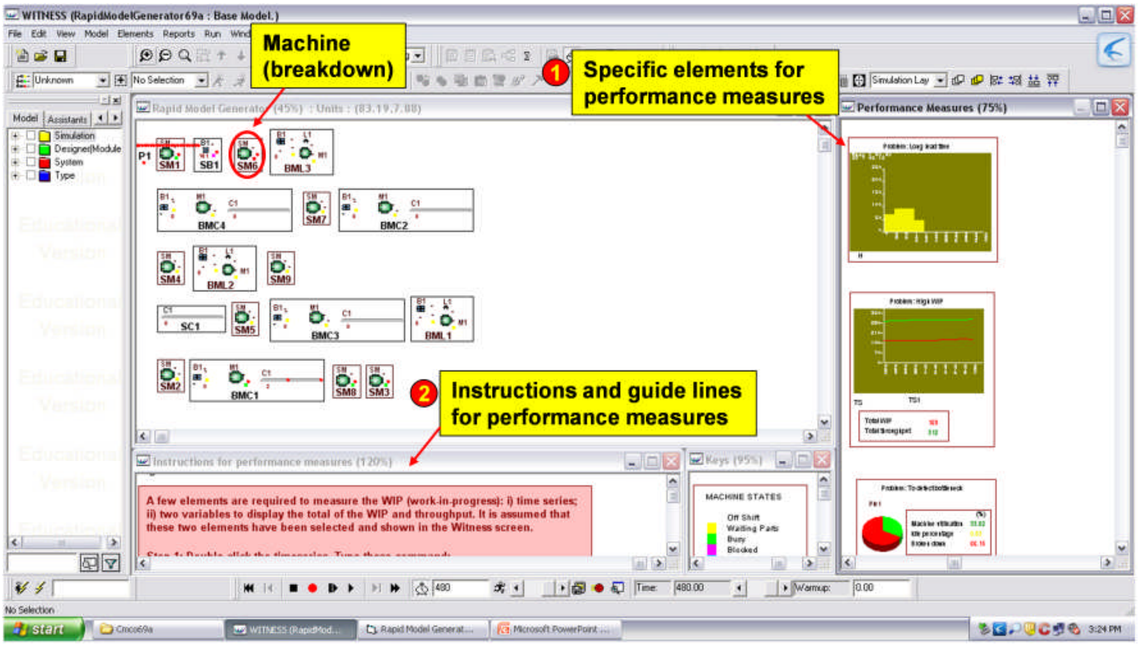

Figure 6-26 Machine breakdown at the beginning of the line

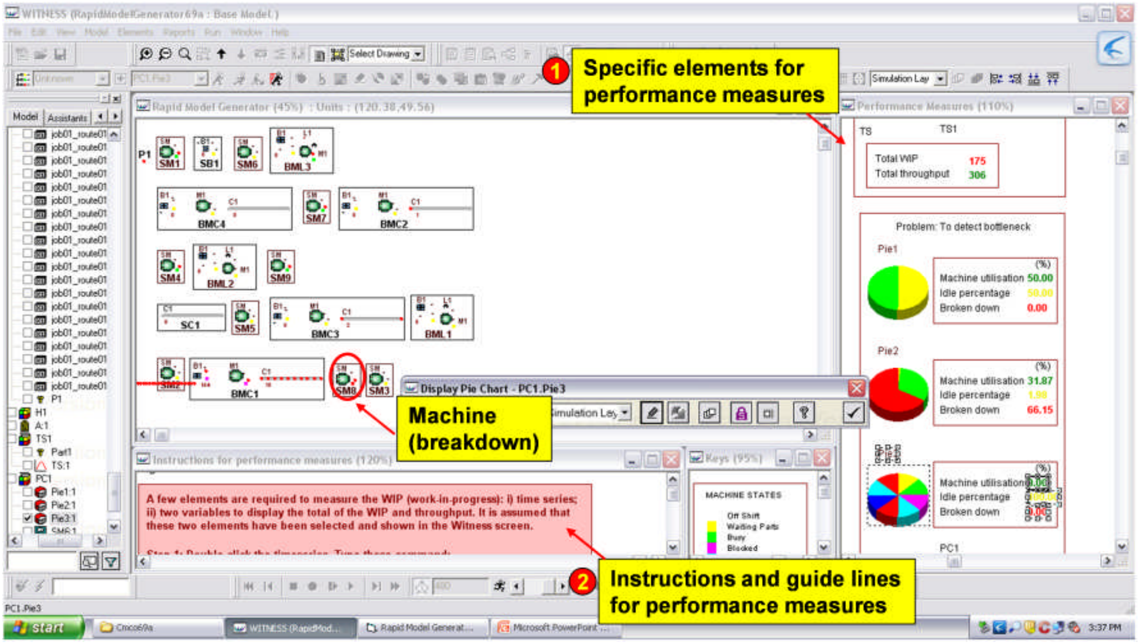

Figure 6-27 Machine breakdown towards the end of the line

<u>Conditions 3 and 4: To measure the effects of machine breakdown when the breakdown is frequent (short MTBF) but the repair time is quick (short MTTF); and breakdown is infrequent (long MTBF) and the repair time is long (long MTTF) against lead time, WIP and machine utilisation.</u>

Figure 6-28 shows the effects of machine breakdown that are related to MTBF and MTTF. The developed prototype provides the specific elements required for the performance measures (number 1) including the instructions and guidelines (number 2). The purpose of this exercise is to compare the effects of machine breakdown against lead time, WIP and machine utilisation based on two conditions: i) breakdown is frequent (short MTBF) but the repair time is quick (short MTTF); ii) breakdown is infrequent (long MTBF) and the repair time is long (long MTTF).

Based on the results, the user can make a decision about which condition will benefit the production line. For each condition, the user can make a comparison in terms of total throughput, amount of WIP, average lead time, average machine utilisation and idle percentage of machines, based on the specific elements (templates) provided by the prototype. The real time simulation results which are graphically presented to the user will facilitate the user in decision making. The simulation results provide some useful information: i) the relationship between the problems; ii) the evolution of the problems; iii) as a reminder of future problems which might arise from the current problem; iv) the current problem cannot be solved until other, related problems are tackled first.

Figure 6-29 shows how the developed prototype facilitates the user in developing an understanding of the established problems and providing the elements or templates to carry out performance measures. Apart from that, the developed prototype facilitates the user with the decision paths to be made based on the established cladogram and current problems faced by the user. Based on the evolution of established problems, the user can visualise a picture of future problems as a consequence of the current problem and take appropriate or preliminary actions in order to solve those problems. The developed prototype provides the required elements (templates) that will facilitate the user in simulating the established problems graphically and obtain the results in real time.

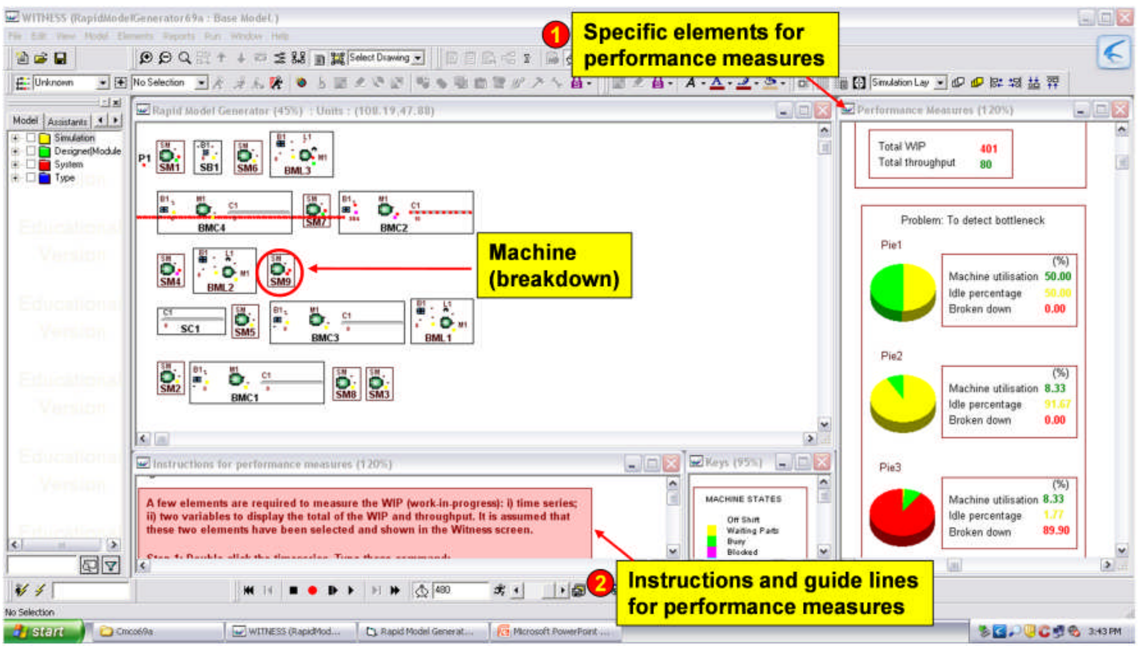

Figure 6-28 Machine breakdown, MTBF and MTTF

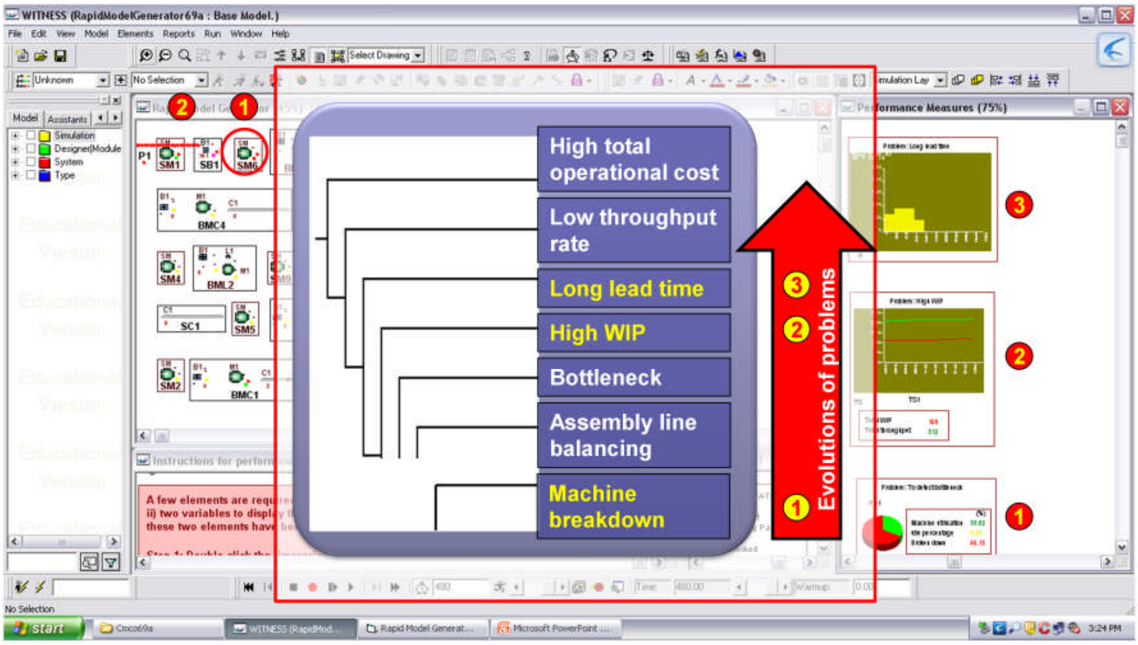

Figure 6-29 Evolution of problems and templates of performance measures

6.5 Chapter summary

The main objective of this chapter is to show the research methodology and framework used to develop the proof-of-concept prototype. The development consists of two phases: i) Phase 1 (templates or modules development); ii) Phase 2 (user interface or control panel development). Phase 1 focuses on how the classification of problems established from the cladogram is translated in the form of templates or modules. Phase 2 presents the details of control panel development using Visual Basic software and how to integrate the output established from the control panel to the Witness environment. Apart from that, this chapter shows the features available, capabilities and output established from the developed prototype.

The testing and validation that have been carried out to prove that the developed prototype can have a significant impact on facilitating the user in simulation modelling and reduce the time for model building based on research methodology proposed, will be presented in Chapter 7.

7 TESTING AND VALIDATION

This chapter focuses on the testing and validation performed in this research, which is to test and validate the developed prototype, and to check that the aim and objectives have been achieved. Validation has been carried out using the expert judgement method, where the developed prototype was tested by users who were experienced in simulation model building through a number of exercises. A confirmatory study has also been carried out through feedback forms provided. A trial session in using the prototype was hosted at both Cranfield University and the National University of Malaysia, and participants were asked to use the prototype to develop a model and execute performance measures so that their perceptions of ease-of-use, user friendliness and usefulness of the prototype could be captured.

The testing and validation sessions were attended by seven participants including four Masters students and three PhD students. The main criteria that have been used in selecting participants for the testing and validation process are that i) the participants should be familiar with Witness simulation tool; and ii) the participants have some experience of model building and simulation.

This chapter has been organised into five sections. Section 7.1 discusses the method that has been carried out to test and validate the prototype. Section 7.2 focuses on the selection of participants. The pilot test and initial feedback for this prototype is presented in Section 7.3. This section also provides the refinements that have been carried out based on the initial feedback. Section 7.4 discusses the actual testing and feedback received. This section also focuses on the analysis and discussion of results based on the testing and validation that have been performed. Apart from that, strengths, weaknesses and further improvements of the prototype are also presented. Section 7.5 provides a summary of this chapter.

7.1 Method of evaluation

The main objective of this chapter is to test and validate the prototype based on user evaluation using the expert judgement method. This validation is not going to measure how good the users are in using the simulation tools but to find out to what extent this prototype can help users to develop a model based on templates (modules) provided, linking the templates, running the simulation and performing some measures based on the scenarios provided.

In order to collect feedback from the users, one-to-one personal evaluations have been carried out. Users were required to do some exercises using the simulation tool which is called Witness. There are two modes for the exercises: i) first, the users are required to do the exercises manually using Witness software; ii) second, the users are required to do same exercises using the prototype that has been developed. The prototype has a user interface (control panel) that is linked to the Witness simulation tool. The time is recorded for each user to complete the exercises and feedback forms have been used to evaluate the usefulness of the prototype.

7.1.1 Evaluation criteria

The evaluation criteria for the testing and validation of this prototype are based on a number of factors:

- A simulation model can be built rapidly and easily
- Easy to link the templates (modules) and run the model
- Easy to change and make a new route
- Easy to switch ON/OFF any elements or templates (modules)
- Easy to do the performance measures
- Capability to define the evolution of problems based on the simulation performed

- Visual appearance of the templates (modules) and elements are understandable

7.1.2 Evaluation and feedback forms

The evaluation consists of two main sections: i) Exercises; ii) Feedback forms: question statements with different response ratings with a personal comments section. The exercises have two modes or scenarios: i) Mode A: Building a model manually using Witness; ii) Mode B: Building the same model using the prototype. Each mode provides three similar exercises and users are required to give personal evaluation in the form of a rating for each exercise. The rating ranges from 1 to 6. Number 1 is recorded as strongly difficult, 2 as difficult, 3 as somewhat difficult, 4 as somewhat easy, 5 as easy and 6 is strongly easy. The purpose of this rating is to evaluate and ensure that the exercises are in the range that can be answered by the participants. These results are very important to make sure that the level of the exercises provided is neither too complicated nor too easy to be answered. Each mode has three similar exercises and times will be recorded for each exercise. The purpose of time recording is to compare the time taken by the participants in completing each exercise in Modes A and B. The results can be used as evidence to see whether the proof-of-concept prototype is capable of helping the user to rapidly build a simulation model. Apart from that, the personal evaluation is used to capture the relationship between users' perceptions for each exercise provided, model building, and the time recorded. For example: if the personal evaluation of a user for exercise 1 in Mode A (building a model manually using Witness simulation tool) is 6 (strongly easy), the user is expected to complete the exercise in a short period of time. But if the time recorded shows that the user has taken takes a lot of time to complete the exercise that means the process of model building is not as easy as expected. Examples of the exercises can be seen in Appendix C.

Users are required to fill out the feedback forms after they have completed all exercises. The rating that has been used for the question statements in feedback forms ranges from 1 to 6 where 1 is rated as strongly disagree, 2 as disagree, 3 as somewhat disagree, 4 as somewhat agree, 5 as agree, 6 as strongly agree. Those question statements and ratings can be used as an indicator to measure to what extent the developed prototype can help the user in model building. In addition, users' perceptions of ease-of-use, user friendliness and usefulness of the prototype can be captured. An example of the feedback forms is shown in Appendix D.

7.1.3 The exercises

<u>Exercise 1</u>

In this exercise, participants were required to build a model, linking the elements and run the model based on the layout provided, as shown in Figure 7-1.

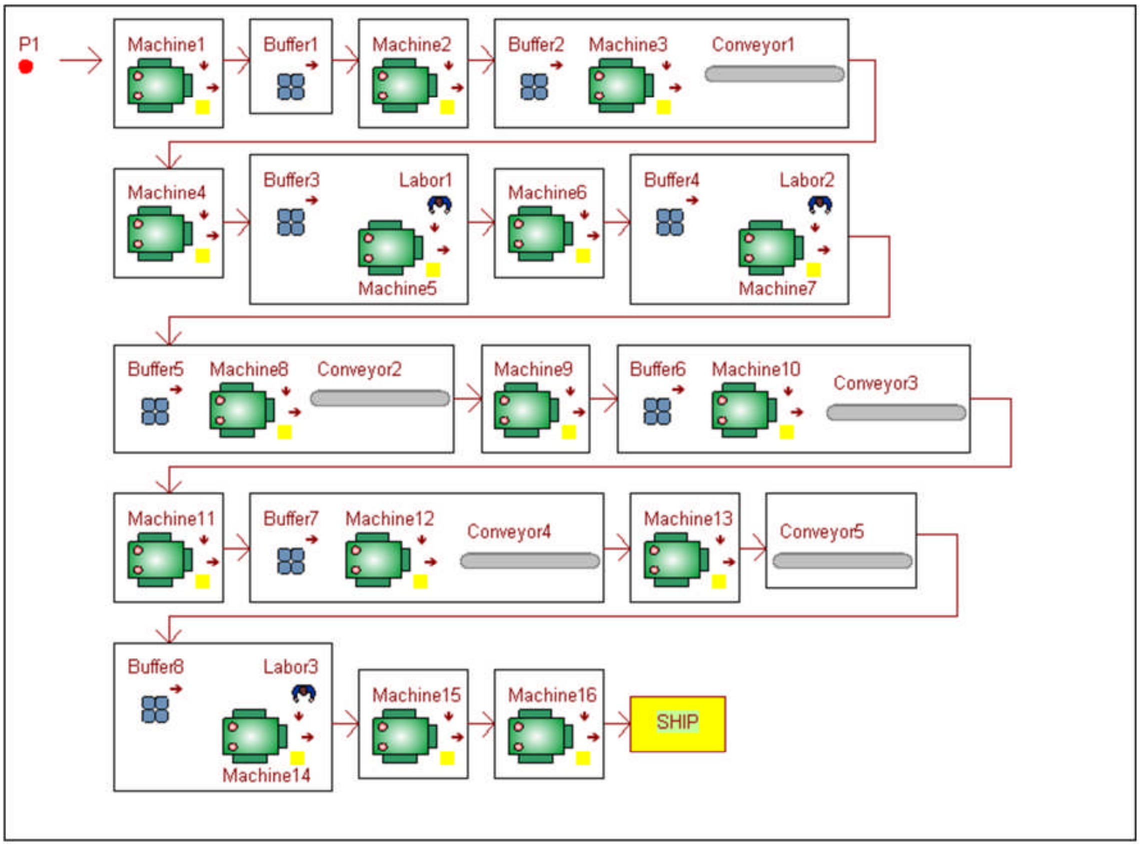

Figure 7-1 Layout

Table 7-1 Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Elements required are: 1 part, 16 machines, 8 buffers, 5 conveyors and 3 labourers. Participants need to provide those elements, position each of them based on layout required, linking the elements and run the model based on the information provided, as shown in Table 7-1. Time will be recorded starting from model building until the participant runs the model without any faults.

Exercise 2

This exercise consists of two sections. In Exercise 2(a), participants are required to rearrange the position of elements based on the layout required, as shown in Figure 7-2, linking them and running the model. In Exercise 2(b), participants are required to make some changes to the current route as the part needs to bypass some of the elements, as shown in Figure 7-3. Therefore, the participants need to break some links in the current route and link them again in order to run the model. Time is recorded for both exercises.

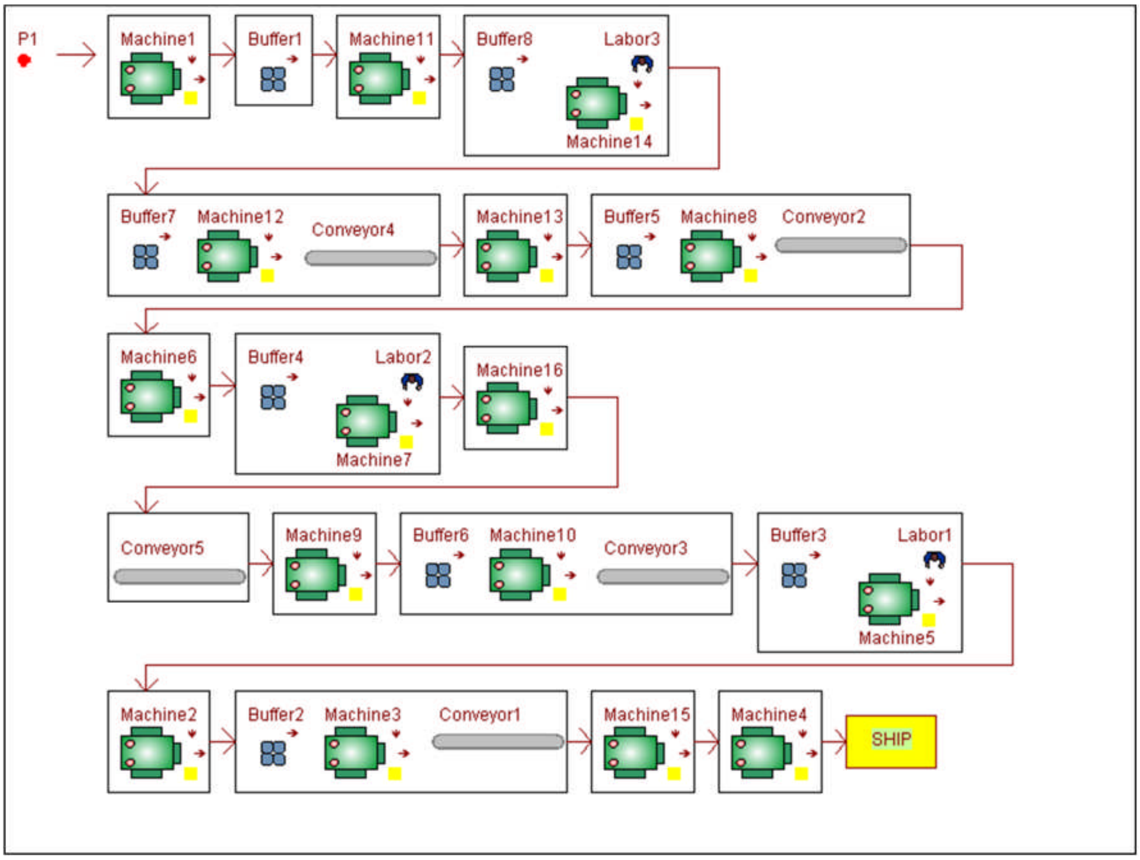

Figure 7-2 New layout

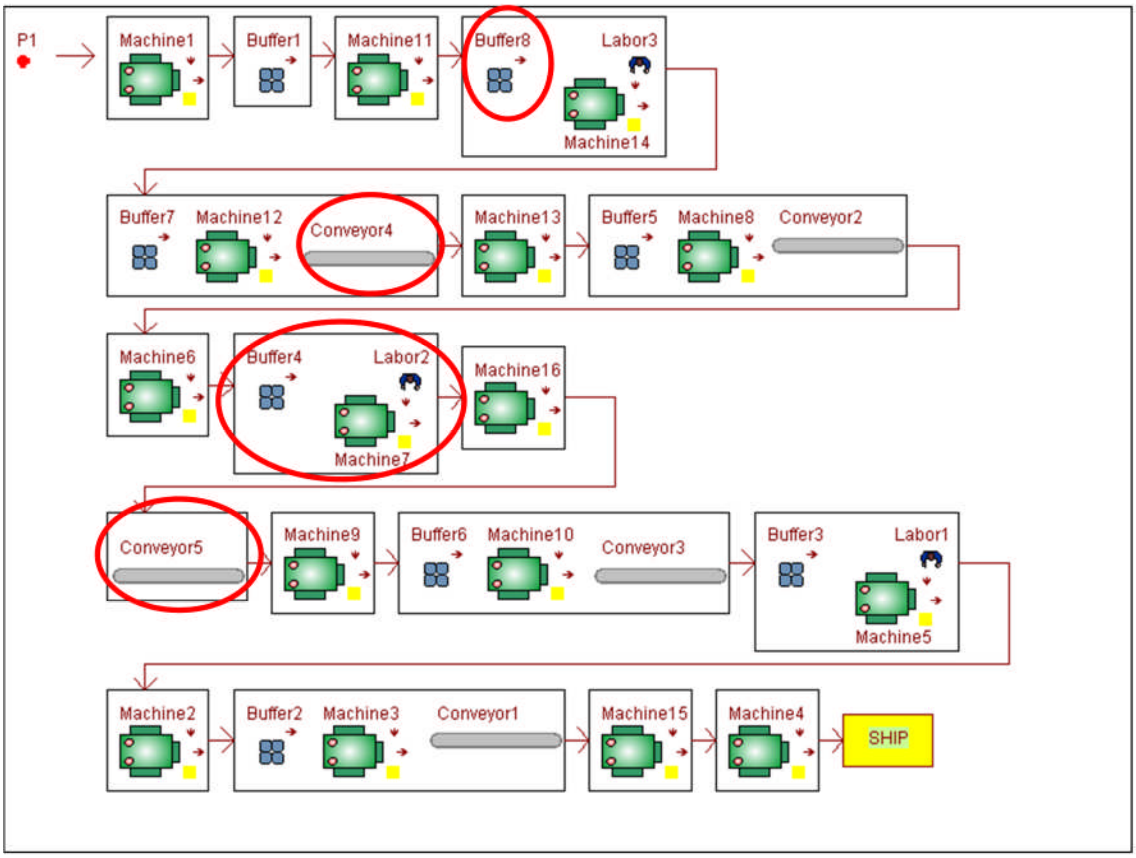

Figure 7-3 Changing the routing

<u>Exercise 3</u>

This exercise addresses the performance measures that need to be performed by the participants based on the layout required from the previous exercise. In Exercise 3a, two different scenarios are provided, as shown in Figure 7-4: i) machine breakdown at the beginning of the assembly line; ii) machine breakdown towards the end of the line. Element details for machine breakdown need to be updated, as shown in Figure 7-5. Participants are required to find out how these two scenarios affect the lead time, WIP and machine utilisation by using a histogram, time series and pie charts.

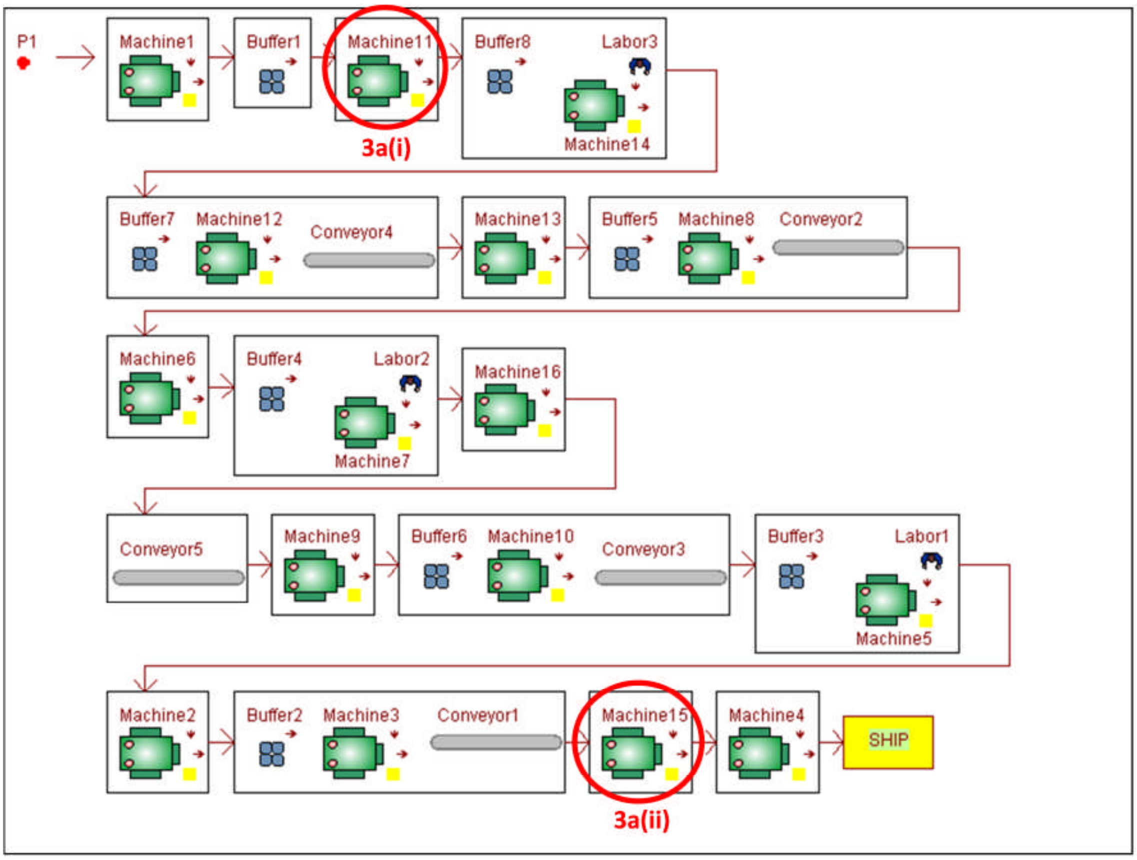

Figure 7-4 Exercise 3a

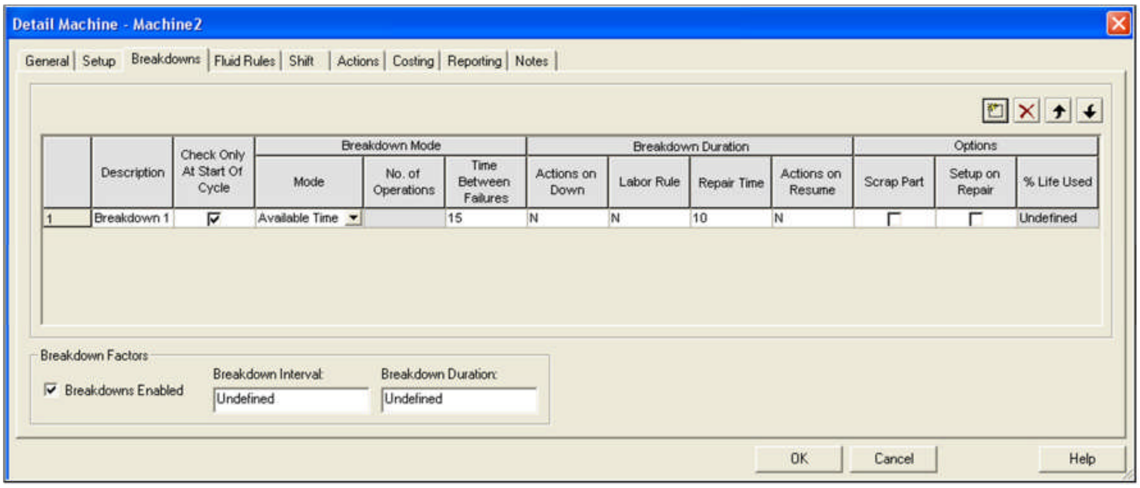

Figure 7-5 Data for machines breakdown

In Exercise 3b, participants are also required to compare the effects of one machine which breaks down in the middle of the assembly line, as shown in Figure 7-6. Two different scenarios are provided: i) breakdown is frequent (short

MTBF) but repair time is quick (short MTTF); ii) breakdown is infrequent (long MTBF) and repair time is long (long MTTF). Element details for machine breakdowns need to be updated for each scenario based on the information provided. Participants are required to find out how these two conditions may affect the lead time, WIP and machine utilisation.

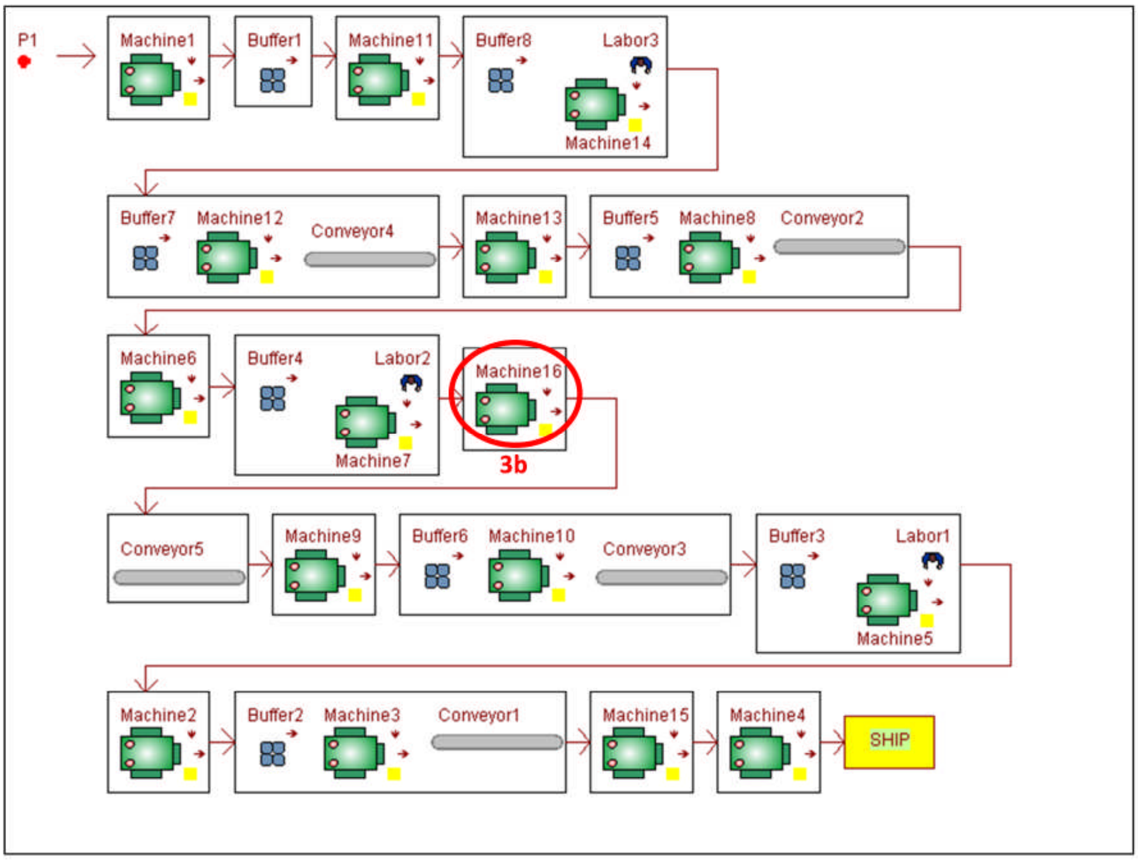

Figure 7-6 Exercise 3b

Since all participants are familiar with the Witness simulation tool, they are required to use some basic elements for performance measure purposes: i) histogram to display the average lead time; ii) time series to plot the amount of WIP over the time; and iii) pie charts to display the average of machine utilisation as well as idle percentage and broken down percentage of the machine. Time is recorded for both exercises.

7.1.4 Feedback forms

Questions 1 and 2 are related to user experience in the simulation modelling area and Witness software, as shown in Figure 7-7. One of the participants' criteria required for testing and validation is experience in using the Witness simulation tool and model building. The purpose of these questions is not only to segregate the participants' experience in using the Witness simulation tool but also to produce unbiased results between the two mode exercises: i) Mode A: Building a model manually using Witness; ii) Mode B: Building the same model using the prototype. In other words, it is unfair to ask participants to take part in the testing and validation process if they do not have any experience in using Witness and model building. Those questions can also be used to prove that model building is not an easy task even though the participants are experienced in using the Witness simulation tool and model building. In addition, both questions are used to prove that simulation tools are not as easy to use as expected and require a lot of experience, specific training, skills and knowledge.

1. **User experience**

How long have you been involved in simulation and model building area?

Never	0 – 6 month	7 – 12 month	More than 12 month	No longer

2. **Usage of Witness software (please tick)**

During lectures only	
During group project	
During thesis project	
Before I came to Cranfield University	

Figure 7-7 Questions 1 and 2 in feedback forms

Question 3 is focused on an ease-of-use evaluation of the prototype, as shown in Figure 7-8. Some features have been taken into account during the development of the prototype, such as user friendliness and the instructions provided being easy to read and understandable.

3. <u>Ease of use</u>

	Strongly Disagree					Strongly Agree
The prototype is easy to use	1	2	3	4	5	6
The instructions are easy to read and understandable	1	2	3	4	5	6

Figure 7-8 Question 3 in feedback forms

Question 4 concentrates on the usefulness of the prototype in terms of model building, as shown in Figure 7-9. The purpose of the questions is to measure to what extent the prototype can help the users in model building and reducing the model development time. All questions have been designed based on six criteria: i) creating the physical elements; ii) linking the elements; iii) running the model; iv) changing the routing; v) implementing performance measures on problems established; vi) facilitating users in model building and reducing model development time.

Question 5 is based on the visual appearance of the prototype, as shown in Figure 7-10. This includes the design of the user interface, graphics and colours, and icons of elements used in the prototype. This information is very useful for the future refinement of the prototype.

4. **Usefulness**

	Strongly Disagree					Strongly Agree
The prototype will help me in model building	1	2	3	4	5	6
The prototype will help reduce time for model building	1	2	3	4	5	6
I can create the physical elements easily and faster	1	2	3	4	5	6
I can link the elements and run the model easily	1	2	3	4	5	6
I can switch ON/OFF any elements, link them again and run the model easily	1	2	3	4	5	6
I can easily measure the performance of the system (throughput rate, WIP, etc.)	1	2	3	4	5	6
All the elements provided for the performance measures are useful	1	2	3	4	5	6
The prototype has a lot of potential in improving model building	1	2	3	4	5	6
I will recommend this prototype to my colleagues	1	2	3	4	5	6

Figure 7-9 Question 4 in feedback forms

5. **Visual appearance**

	Strongly Disagree					Strongly Agree
The prototype displays visually pleasing design	1	2	3	4	5	6
Graphics and colour detract from actual content	1	2	3	4	5	6
The icons of the elements are easy to understand	1	2	3	4	5	6

Figure 7-10 Question 5 in feedback forms

Question 6 provides space for participants to give opinions and suggestions regarding the development of the prototype or other issues related to the validation process.

7.2 Selection of participants

This section addresses the criteria that have been used in selecting suitable candidates for the testing and validation process.

7.2.1 Selection criteria

The following criteria have been taken into account to guide the selection of participants for the testing and validation process:

- The participant should know how to use Witness software
- The participant has some experience of model building and simulation

Since the prototype has been developed using Witness software, the participants are required to have some knowledge in using that software. The level of skill or experience is not a requirement to be involved in the validation process because the purpose of this section is not going to measure how good the participants in using the software but to what level the developed prototype can help the participants in model building. In other words, beginners, intermediates and experts in Witness can take part in this validation process. If the participant has one of these criteria: i) has no experience using Witness software but has knowledge in model building and simulation; or ii) has experience using other simulation software but has knowledge in model building and simulation, this kind of participant will not be required to take part in the validation process because the results might be biased towards the developed prototype. Moreover, the exercises provided have been moulded in the Witness environment and people who are not experienced in using Witness will face many difficulties in performing the exercises.

7.3 Pilot testing and feedback

The pilot test was conducted on 8th July 2010. One PhD student was selected for this pilot test as she is familiar with simulation modelling, especially using Witness software. This test provides the opportunities to the researcher to have direct communication, in-depth understanding about the feedback and concerns can be raised regarding the exercises and the prototype. Therefore, possible changes can be performed before the real test and validation.

7.3.1 Pilot testing: results

Times have been recorded for the pilot testing and the results are shown in Table 7-2.

Table 7-2 Results from the pilot testing

Mode A: Building a model manually using Witness

	Time (min)	**Evaluation**
Exercise 1	15	6 (very easy)
Exercise 2	24	2 (difficult)
Exercise 3a(i)	Participant could not complete the exercise	3 (somewhat difficult)
Exercise 3a(ii)	Participant could not complete the exercise	3 (somewhat difficult)
Exercise 3b(i)	Participant could not complete the exercise	5 (easy)
Exercise 3b(ii)	Participant could not complete the exercise	5 (easy)

Mode B: Building the model using the prototype

	Time (min)	**Evaluation**
Exercise 1	9	6 (very easy)
Exercise 2	8	6 (very easy)
Exercise 3a(i)	5	4 (somewhat easy)
Exercise 3a(ii)	Participant could not proceed with the exercise	
Exercise 3b(i)	Participant could not proceed with the exercise	
Exercise 3b(ii)	Participant could not proceed with the exercise	

The results show that the pilot test was not completed for the following reasons:

- The participant took a lot of time in performing all the exercises in Mode A (building the model manually using Witness). The participant had spent 62 minutes for all exercises in Mode A and the time recorded did not take into account all of Exercise 3 that could not be completed. The pilot testing for Mode A had to be stopped to give some space to the participant to perform exercises in Mode B even though the participant was still trying to complete Exercise 3 in Mode A.

- The participant could not completed Exercise 3 in Mode A because she did not know how to measure the lead time, WIP and machine utilisation using specific elements such as histogram, time series and pie charts. Since the participant had spent too much time for all exercises in Mode A, she just had enough time to finish Exercises 1, 2a, 2b and 3a(i) for Mode B (building the model using prototype) before she had to leave and did not finish the pilot testing. That is why the participant could not proceed with the next exercises. The participant took only 22 minutes to finish some of the exercises (as mentioned above) in Mode B. Therefore the total time taken by the participant for the pilot test is 84 minutes. Even though the participant could not complete all the exercises in Mode B, the feedback and results are still valid for the analysis of the research because nearly three quarters of the exercises have been completed. Moreover, Exercises 3a and 3b are still focusing on same topic which is performance measures. The differences are only on the location of the breakdown machines and data required for each scenario but the approach to measure the scenarios such as lead time, WIP and machine utilisation are still similar.

The results of the evaluation for the exercises in Mode A (Table 7-2) show that the participant has ranked Exercise 1 as strongly easy and Exercise 2 as difficult. Since the participant has basic knowledge in Witness, she will not face any problems in providing all the physical elements based on the required layout, linking them, and running the model. Exercise 2 is also a straightforward question which requires the user to rearrange the current elements and link them again. There is no additional physical element or logic required in this exercise. The participant for the pilot testing found this exercise difficult because she made a lot of mistakes and became confused during rearranging the physical elements, and logic errors occurred when using the pull/push functions. The participant has ranked Exercise 3 as somewhat difficult and easy. It was difficult because the participant did not know how to perform the performance measures using the required elements such as histogram, attribute, time series, PUTIL function and pie charts. Since the evaluation form which was carried out during the pilot test did not require the participant to use any specific elements for the performance measures, the participant had taken the easiest way by referring the statistics report in Witness to answer all the questions in Exercise 3 manually. That is why the participant has ranked this exercise as easy because she knows where to get the statistics report from and she knows how to use this report to get the answers manually through calculation. Even though the answers are correct, they was not accepted because the question has been customised to measure the level of difficulty in model building through practicality among modellers and it is not based on only correct answers.

In Mode B, the participant has evaluated the exercises ranges between 3 (somewhat easy) to 6 (strongly easy). The participant found that it was quite easy to perform those exercises using the prototype because it had been designed and developed with some functions to facilitate users in model building so as to reduce the model development time.

7.3.2 Pilot testing: analysis of feedback

The response is analysed based on two factors: i) feedback forms; and ii) direct communication with the participant.

1. Analysis of feedback forms

Based on the feedback forms received, the participant had experience in the simulation and model building area for more than 12 months and she had experience in using Witness software before she came to Cranfield University.

Apart from that, the ease-of-use criterion for this prototype has been proved by the participant as easy to use. The usefulness criterion was intended to prove the developed prototype is very useful in helping the user in model building. Based on the feedback received, the participant has strongly agreed that the prototype could reduce the time in model building and that all the elements provided for the performance measures are useful. In addition, the participant also agreed that she could create the physical elements, linking them, running the model and performing the performance measures easily and faster by using this prototype. The overall feedback from the pilot testing on the usefulness of the prototype shows that the prototype is very useful and has a lot of potential in improving model building.

In terms of visual appearance, the participant has rated the visual display of the prototype as 3 or somewhat disagree. Apart from that, the participant's perceptions on the graphics, colour and icons of elements was somewhat good with a rating of 4 (somewhat agree). Based on the discussion with the participant, these issues have been raised due to a few factors which will be discussed in the next section.

2. Analysis and feedback of prototype

<u>Visual appearance</u>

Apart from the evaluation using the feedback forms, observation and discussion with the participant were conducted during the pilot testing. The purpose of these activities is to identify any drawbacks or weaknesses that can be tackled before the real test and validation. As mentioned in the previous section, a few issues have been raised regarding the visual appearance of the prototype as listed below.

- The icons used for the elements were too small and it was difficult for the user to identify those elements

- The name of each element was too small and it was difficult for the user to identify and rearrange them

- The instructions provided were too small and difficult for the user to read

- The windows for the physical elements and performance measures on the Witness screen were also small

- Each element was positioned vertically. This was the default layout that was automatically generated by the prototype on the Witness screen. Therefore, the user needs to scroll down the screen window each time to re-position the elements.

All of these issues are illustrated in Figure 7-11.

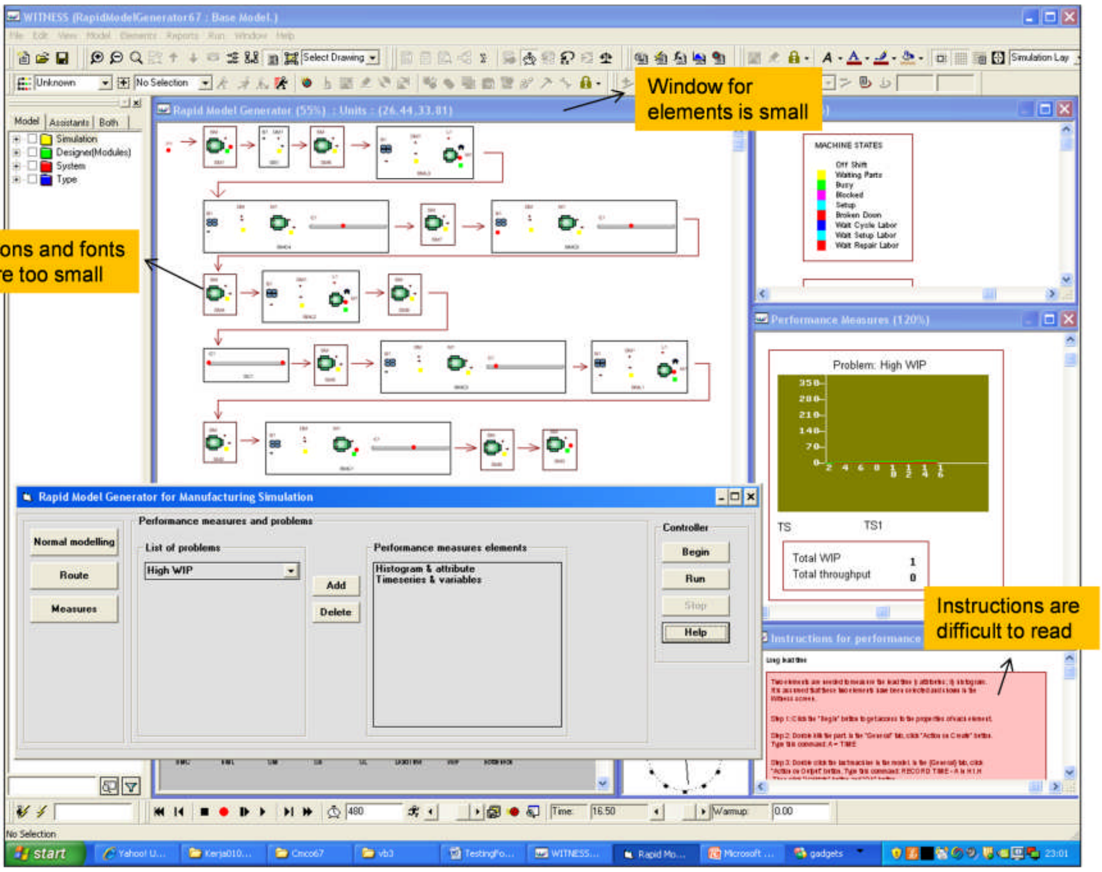

Figure 7-11 Visual appearance and issues: size for icons and fonts

<u>Performance measures and logics</u>

Based on observations made by the researcher, the participant needed to type the logics in some elements of the templates manually, especially in Exercise 3 (performance measures).

<u>Prototype (control panel)</u>

In this section, a few issues have been found based on observations during the pilot testing:

- One more button is needed in a few sections of the control panel. The function of this button is to help the user to delete all unwanted elements in one click.

- Witness screen is disabled each time the user runs the model from the control panel. The user needs to click the “Begin” button each time to gain access to the Witness properties.

- The “Routing summary” section in the control panel is disabled when the user has chosen the route for the part. Therefore the user could not gain access to this section any more. In other words, they could not change the route at all if they have passed this section.

The details of these issues will be extensively presented in the next section.

7.3.3 Refinement of the pilot testing

The purpose of this section is to list all the improvements or changes that have been performed based on the refinement suggestions obtained from the previous section. These refinement suggestions and improvements are very important to ensure that the process of validation can be done smoothly in order to obtain good results.

<u>Refinement 1: visual appearance</u>

A new visual appearance has been designed based on the initial feedback received from the pilot testing. The font size for the names of each icon and the instructions, and icons’ size have been increased in order to help the user to see the physical elements more clearly, as shown in Figure 7-12. The window size for the physical elements and performance measures on the Witness screen has also been increased. As a result, the users do not have to scroll down too many times in order to have a full view of the physical elements. In addition, identical elements will be positioned vertically as a group. The groups of elements will be positioned horizontally. This layout is generated automatically and dynamically by the prototype in the Witness screen, based on the calculation of the 2D (two dimensional) coordinates, as shown in Figure 7-13.

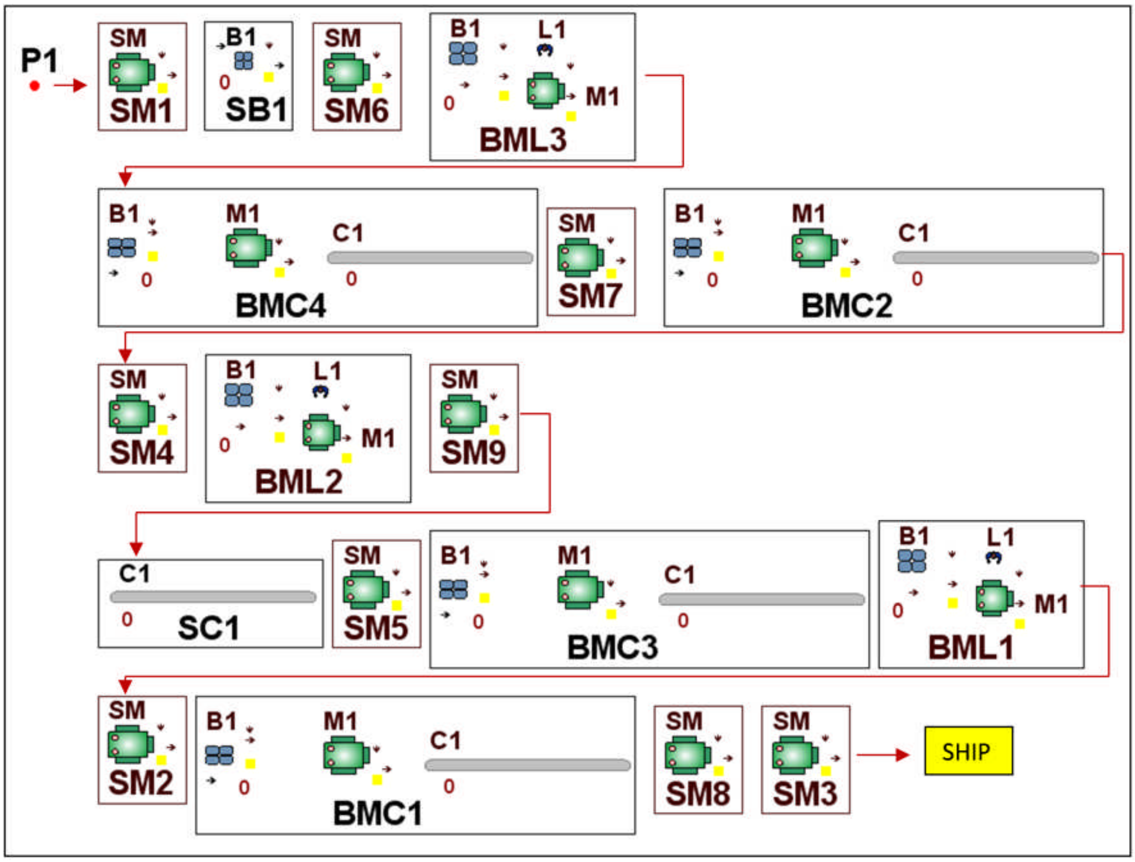

Figure 7-12 Changes in visual appearance

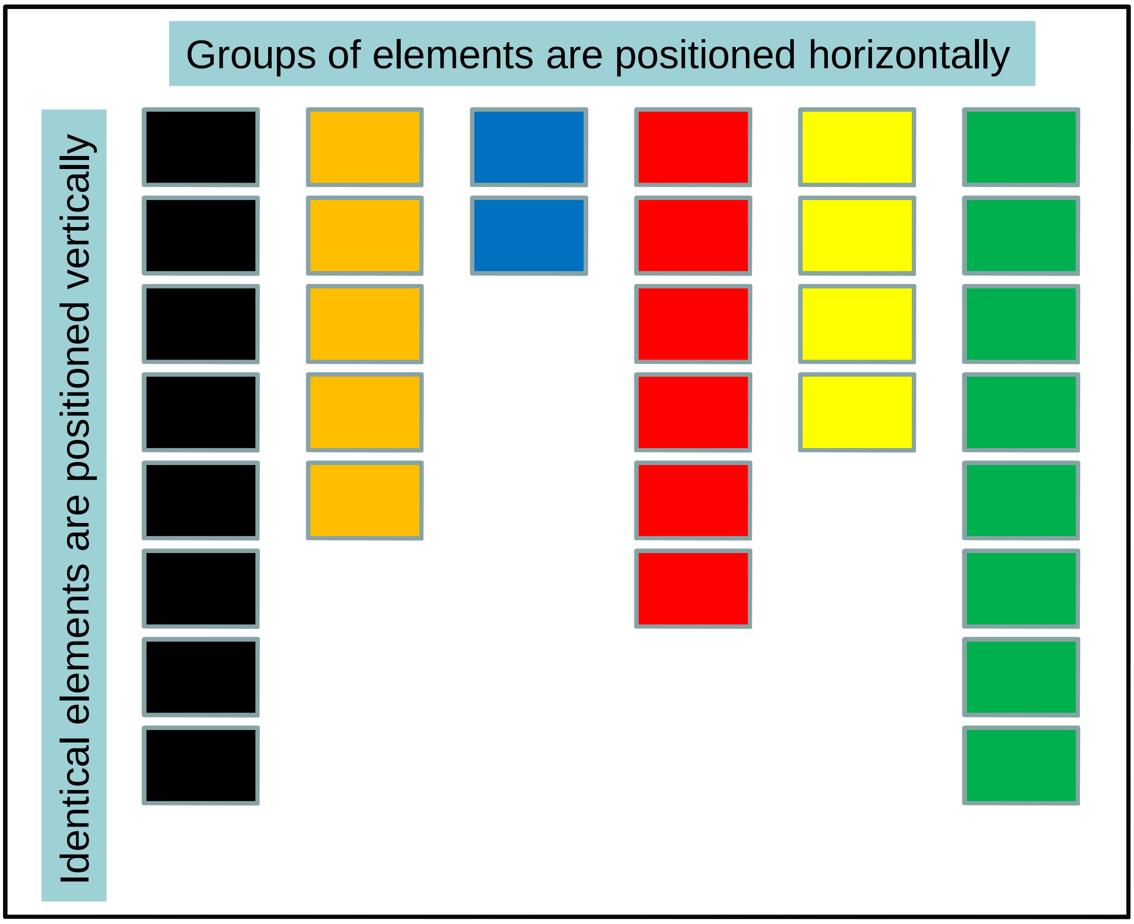

Figure 7-13 Default layout of elements automatically generated by the prototype

Refinement 2: prototype (control panel)

One additional button has been created in the “Normal modelling” scenario (elements section, routing summary section) and “Routing” scenario (switch ON/OFF elements section). This button is named “Delete all” and its function is to delete all unwanted elements in one click. Therefore the user does not have to click the “Delete” button each time to delete the elements. Figure 7-14 and Figure 7-15 show the changes that have been performed which can help the user in model building using the prototype. The list box on the right shows the list of destinations or routing for a part based on user input. If the sequence of destinations for the part is wrong and the user wants to clear up the destination list, they just need to click the “Delete all” button instead of the “Delete” button.

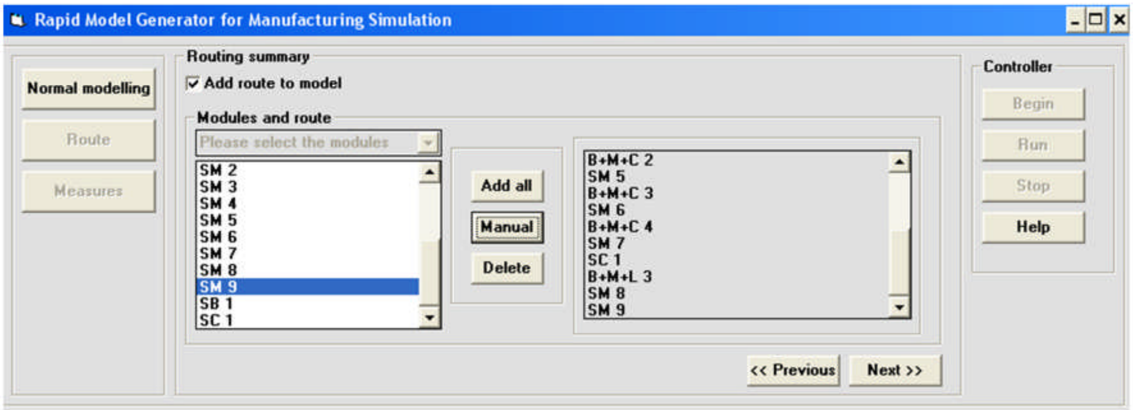

Figure 7-14 Before refinement

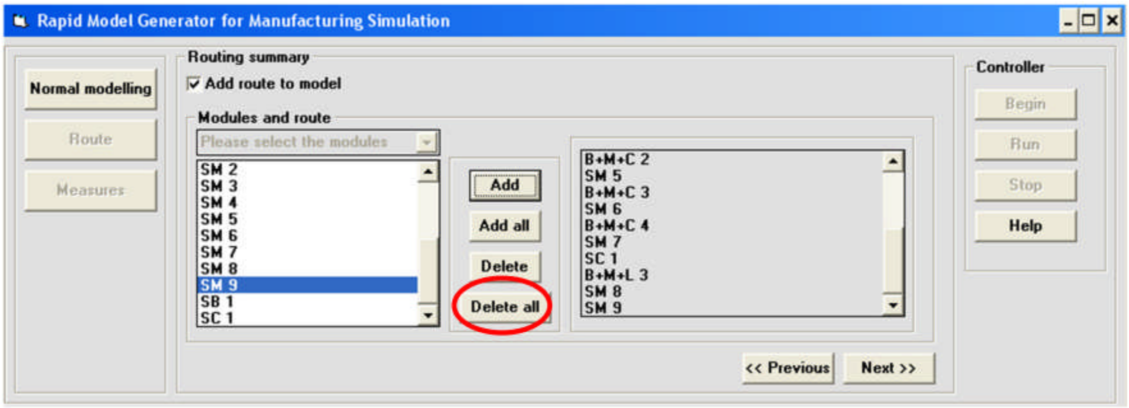

Figure 7-15 After refinement

In addition, some modifications have also been made to the prototype which enabled the Witness screen all the time and the user can control or gain access to the Witness environment by using the control panel or Witness properties.

Other than that, some more modifications have been made to the prototype to ensure that the “Routing summary” section is enabled all the time and the user can make any changes to the list of destinations for the part. Once the user makes any changes in the “Routing summary”, other sections that use this information will be updated automatically.

<u>Refinement 3: specific elements for performance measures</u>

In Questions 3a and 3b, participants are required to measure the effects of machine reliability (breakdown) against lead time, WIP and machine utilisation based on the scenarios provided. They are required to use specific elements: i) attribute and histogram (lead time); ii) time series (WIP); and iii) pie charts (machine utilisation, idle percentage and breakdown percentage). Since the aim of this validation process is to measure to what extent this prototype can help the user in model building, practising the specific elements in these exercises can be observed as one way to investigate the knowledge of the user in simulation and model building. Therefore a comparison can be carried out between practising those elements manually and using the prototype.

7.4 Validation and feedback

A few sessions of testing and validation for the developed prototype have been carried out, as shown in Table 7-3. The sessions were conducted on 13th July, 26th July and 17th August 2010 at Cranfield University, which was attended by seven participants including four Masters students and three PhD students. Another session has been conducted at the National University of Malaysia with the participation of two Masters students.

Table 7-3 Number of responses

Participant	Date
4 Masters students	Tuesday 13th July 2010
1 PhD student	Monday 26th July 2010
2 PhD students	Tuesday 17th August 2010
2 Masters students	Thursday 25th November 2010

7.4.1 Analysis of the results

Table 7-4 shows the results of times that have been recorded for each participant and the evaluation of the exercises. The results show that participants have spent more time building the model using Witness compared to the prototype with an average time of 21.5 minutes for Exercise 1 and 23 minutes for Exercise 2. The average time for doing the same exercises using the developed prototype is around 7.11 minutes and 4.89 minutes, respectively. The gap of time recorded between these two modes of exercises shows that the prototype can reduce the model development time significantly, especially in creating the physical elements or templates and linking all the elements in order to run the simulation process for the model being developed.

The results also show that all the participants could not complete some of the exercises in Mode A such as Exercises 3a(i), 3a(ii), 3b(i) and 3b(ii). The participants could not complete those exercises because they did not know how to measure the lead time, WIP and machine utilisation using the specific elements required such as histogram, time series and pie charts. For Mode B, all of them were capable of completing all the exercises required using the prototype with the maximum and minimum average time of 9.11 and 1.67 minutes, respectively. It can be clearly seen that the developed prototype would benefit the participants, especially in simulation modelling, and at least it has helped the participants to complete all the exercises faster than doing them manually using Witness software.

No time has been recorded for participant four because he did not do the exercises as required in Mode A. This participant did not read the instructions carefully and he misunderstood Exercises 1 and 2, especially in Mode A. He ignored Exercise 1 and went straight to Exercise 2. He was supposed to do Exercise 1 first because the output from this exercise is used in the next exercise. Since there was no time left during the session, and in order to give some of the time available to other exercises, this participant was required to continue with the exercises in mode B.

All participants have given average scores of 74.07% and 70.37% on how easy it is to perform Exercises 1 and 2 manually using Witness software (Mode A). In addition, all participants agreed that those exercises are easy to be completed using the prototype based on the average scores of 96.30% and 97.92%, respectively. Since all the participants could not complete Exercises 3a and 3b (Mode A), they have been given the average scores of 2.38 and 2.25 out of 6 or 39.58% and 37.50%, respectively. Participants 5 and 6 have given their personal response as quite high compared to other participants with an average score of 5 (easy) and 4 (somewhat easy) for Exercises 3a and 3b even though they could not complete both exercises due to lack of practice with Witness software.

All the exercises in Mode B have been rated with an average score between 5.25 (87.50%) and 5.88 (97.92%). Based on the average scores given, all the participants agreed that they managed to complete all the exercises easily and faster than performing the same exercises manually in Mode A. As a conclusion, many of the participants have indicated that the overall results of the proof-of-concept prototype have been very successful for several reasons: i) it is very helpful in simulation and model building; ii) it can reduce the model development time or users can do the model building and simulation quickly; iii) users can do the performance measures easily based on the established problems. The full details of results for all participants can be seen in Appendices E to M.

Table 7-4 Results of validation (time recording and exercises evaluation)

Mode A: Building a model manually using Witness

	Participants and time recorded (minute)									Average
	P1	P2	P3	P4	P5	P6	P7	P8	P9	time (minute)
Exercise 1	16	11	21	Nil	16	24	15	42	27	21.50
Exercise 2	15	14	27	Nil	18	22	13	39	36	23.00
Exercise 3a(i)	Participants could not complete the exercises									Nil
Exercise 3a(ii)										Nil
Exercise 3b(i)										Nil
Exercise 3b(ii)										Nil

	Exercises and evaluation									Average score	Average score (%)
Exercise 1	6	5	2	3	4	6	6	3	5	4.44	74.07
Exercise 2	5	4	6	3	2	5	6	4	3	4.22	70.37
Exercise 3a	1	2	2	Nil	2	5	4	1	2	2.38	39.58
Exercise 3b	1	2	2	Nil	2	5	4	1	1	2.25	37.50

Mode B: Building the model using prototype

	Participants and time recorded (minute)									Average
	P1	P2	P3	P4	P5	P6	P7	P8	P9	time (minute)
Exercise 1	6	9	7	3	5	9	7	11	7	7.11
Exercise 2	5	7	5	3	4	4	5	7	4	4.89
Exercise 3a(i)	9	2	9	4	7	12	9	15	15	9.11
Exercise 3a(ii)	4	1	4	6	3	3	3	7	7	4.22
Exercise 3b(i)	4	1	3	3	2	6	2	4	5	3.33
Exercise 3b(ii)	1	1	2	3	1	1	1	3	2	1.67

	Exercises and evaluation									Average score	Average score (%)
Exercise 1	5	5	6	6	6	6	6	6	6	5.78	96.30
Exercise 2	Nil	6	6	6	5	6	6	6	6	5.88	97.92
Exercise 3a	Nil	4	5	6	5	6	5	6	5	5.25	87.50
Exercise 3b	Nil	5	6	5	5	6	6	6	6	5.63	93.75

7.4.2 Analysis of the feedback

The response is based on the feedback forms received. This section discusses a few aspects that have been used to measure to what extent this prototype can help the user in model building. The full details of results (feedback) for all participants can be seen in Appendices E to M.

1. Participant profiles

Figure 7-16 shows that five participants had 0-6 months of experience in simulation and model building. Only two had 7-12 months of experience in simulation modelling and the other two had more than 12 month' experience in simulation modelling. Table 7-5 shows that only one participant had experience of using the Witness simulation tool before coming to Cranfield University. Most of the Masters students learnt about simulation modelling using Witness during lectures. Some of them had learnt about model building in Witness during thesis projects and group projects. Generally, all of them are experienced in simulation and model building using the Witness simulation tool. In other words, all of them have the basics and fundamental knowledge for using Witness for simulation and model building. In addition, these students, to some extent have had industrial experiences using Witness simulation tool during their group project.

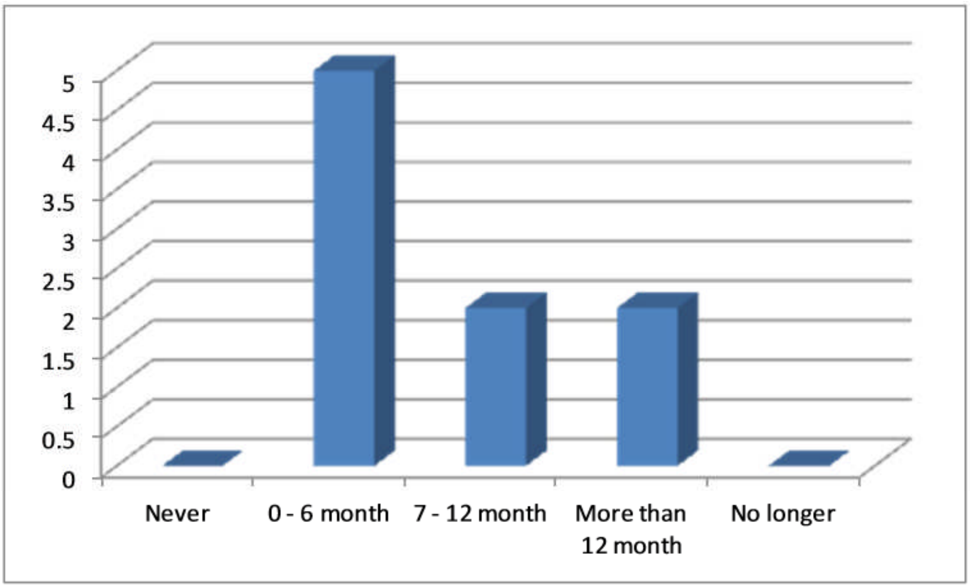

Figure 7-16 Participants' experience in simulation and model building

Table 7-5 Participants' experience in simulation, model building and Witness software

	Participant								
Experience in simulation and model building	1	2	3	4	5	6	7	8	9
Never									
0 - 6 month	•	•	•	•	•				
7 - 12 month								•	•
More than 12 month						•	•		
No longer									
Experience using Witness software									
During lectures only		•	•	•				•	•
During group project	•					•			
During thesis project		•			•		•		•
Before came to Cranfield University							•		

2. Ease-of-use and usefulness

Table 7-6 shows that the ease-of-use criterion is intended to prove how easily the developed prototype could be used in model building based on the total average percentage of 88.89% for all participants. An average score of 5.10 or 85% has been given by participants who have 0-6 months' experience in simulation modelling because they have found that the prototype is easy to use and the instructions provided are easy to read. Those participants who have more than 12 months of experience in simulation modelling also agreed that the developed prototype has achieved both criteria, as mentioned in Question 3, with an average score of 5.25 or 87.50%.

In addition, Table 7-6 shows that all measures of usefulness of the prototype in Question 4 have received positive responses from all participants. The results show that the usefulness of the developed prototype has been given an average score of 5.30 or 88.3%. Only participant three has given a low score rating of between 2 and 3 to four measures of usefulness: i) create elements easily and faster; ii) link and run model easily; iii) switch ON/OFF elements easily; and iv) capable to do performance measures easily. The scores rated by this participant are totally different from the others. It is believed that participant 3 has misunderstood those four measures because he gave the scores based on using Witness simulation tool not the developed prototype. This issue can be seen very clearly in the feedback forms received where this participant has written down the words “using Witness” next to the three measures in Question 4. That is why low scores rating have been given to those measures in that question. Most of the participants believed that this prototype has a lot of potential in improving model building and it is capable of reducing model development time based on the highest average scores given, i.e. 5.56 respectively.

3. Visual appearance

Question 5 consists of a few measures regarding the visual appearance of the prototype. The visual appearance has been given an average score of 4.37 or 72.84%. Graphics and colours used in the prototype have received the lowest average score by the participants with a value of 3.89. Only two participants agreed that the graphics and colours used in the developed prototype are consistent and fine. The author is quite concerned about this average score because the graphics and colours used in the prototype are similar to the Witness environment. The author has used a default value and setting for both of them. Moreover, the lowest average score received did not synchronise with the scores of the other two measures for this question. Therefore a few assumptions are relevant to this incident: i) most of the participants did not read the question carefully; ii) participants were rushing to complete the feedback forms; iii) participants had misunderstood the question.

Table 7-6 Summary of feedback

Experience in simulation and model building	Participant 1	2	3	4	5	6	7	8	9	Average score	Average score of experience 0-6 month	7-12 month	More than 12 month
Never													
0 - 6 month	●	●	●	●	●								
7 - 12 month								●	●				
More than 12 month						●	●						
No longer													
Experience using Witness software													
During lectures only		●	●	●				●	●				
During group project	●					●							
During thesis project		●			●		●		●				
Before came to Cranfield University							●						
Question 3 (ease of use)													
Easy to use	4	5	5	6	5	6	5	6	6	5.33	5.00	6	5.50
Instructions are easy to understand	5	6	4	6	5	5	5	6	6	5.33	5.20	6	5.00
Average score for Question 3										5.33	5.10	6	5.25
Average percentage for Question 3 (%)										88.89	85.00	100	87.50
Question 4 (usefulness)													
Help in model building	5	5	5	6	6	4	5	6	6	5.33	5.4	6	4.50
Reduce time in model building	6	5	5	6	6	5	5	6	6	5.56	5.6	6	5.00
Create elements easily and faster	6	4	2	6	6	5	6	6	6	5.22	4.80	6	5.50
Link and run model easily	6	5	2	6	6	5	5	6	6	5.22	5.00	6	5.00
Switch ON/OFF elements easily	5	5	2	5	5	5	5	6	6	4.89	4.40	6	5.00
Capable to do performance measures easily	4	4	3	5	5	6	6	6	6	5.00	4.20	6	6.00
Provide useful elements for performance measures	5	4	5	5	5	6	6	6	6	5.33	4.80	6	6.00
Potential in improving model building	6	5	5	6	5	6	6	6	5	5.56	5.40	5.5	6.00
Recommend to others	5	5	5	6	6	5	6	6	6	5.56	5.40	6	5.50
Average score for Question 4										5.30	5.00	5.94	5.39
Average percentage for Question 4 (%)										88.3	83.3	99.07	89.8
Question 5 (visual appearance)													
Prorotype displays visually pleasing design	5	4	4	6	5	5	5	4	4	4.67	4.80	4	5.00
Graphics and colours detract from content	4	4	2	5	5	2	5	4	4	3.89	4.00	4	3.50
Icons are easy to understand	4	5	4	5	5	5	5	5	3	4.56	4.60	4	5.00
Average score for Question 5										4.37	4.47	4	4.50
Average percentage for Question 5 (%)										72.84	74.44	66.67	75.00

7.4.3 Strengths of the prototype

Based on the results of the testing and validation, it can be seen that development of the proof-of-concept prototype based on the classification of problems using the cladistics technique and template approach can be one of the options available to help the user in model building and to reduce the model development time.

The developed prototype has its own peculiar contribution in simulation and model development. This can be summarised in three main phases as follows:

- The prototype helps the user in providing the physical elements more easily and faster
- The prototype is capable of generating the route for a part automatically, based on user selection. Apart from that the prototype is able to change the route dynamically. One unique feature is developed in the prototype whereby the user could bypass any elements in the model by turning off the selected elements. At this point a new routing summary is automatically generated in order to run the model. These elements can be switched on again or vice versa. In other words, a new routing summary will be generated automatically and dynamically based on the changes made by the user.
- The prototype also helps the user in providing templates for performance measures. These templates contain specific elements which can help the user to measure scenarios such as long lead time, high WIP, percentage utilisation of bottleneck machinery and high scrap/waste. Therefore any user with a different level of knowledge in simulation modelling or background can use this prototype to build a model and do performance measures.

7.4.4 Weaknesses of the prototype

This section discusses some of the weaknesses of the developed prototype. The purpose of this section is to identify any opportunities for improvement in enhancing the prototype. The weaknesses have been identified as listed below:

Details of elements

- In order to build a model in Witness, the user needs to define the element first, before it can be displayed or detailed. This principle can be explained as follows: i) define (specify the names and quantities of the elements); ii) detail (specify how the element operates, how the inputs to and outputs from an element are controlled, timings and routing of parts as the parts move through the model, logic for controlling the simulation process); and iii) display (how elements in the model are displayed on the screen such as icons, colour, fonts, etc.). In the context of this prototype, the user still needs to detail the element manually by typing some logics in that element's properties in Witness, especially when working with performance measures. This step should be automated unless the user has decided to customise some functions in the element or is detailing the element on their own, as typing is quite tedious and time-consuming. This issue has been noticed by the author throughout the process of the development. The main reason for this issue is that the author still could not find a way to gain access to the element's properties in order to generate the details (logics) automatically from the prototype using Visual Basic. This issue can be a root cause for the other weaknesses as discussed below:

  Other effects

  - Details of elements in templates, especially the logics in controlling the routing of parts, need to be input manually by typing in the logics especially in creating rework stations, parallel lines, etc.

        - Possible refinement: i) Logics will be created by the prototype automatically and all of them will be sent to elements in templates in real time; ii) Creating templates with more complex logics which cover rework stations, parallel lines, etc.

<u>Moving parts between elements</u>

- A routing function has been used in describing the flow of a part through the model. Since the prototype has been developed to facilitate the user in model building, it is expected to provide the route of a part automatically and dynamically. Since the author could not gain access to the element's properties in Witness from Visual Basic, a method of input/output rules using a pull/push function could not be implemented in the prototype. A routing function is used to generate the destinations automatically based on the user's selection in the control panel of the prototype.

    <u>Other effects</u>

    - Based on the route property sheet of a part in Witness, the destinations will be kept in a stage by stage list. Each stage represents one destination. As a result, one part has only one list of destinations or route. Therefore, there is no chance of creating more than one route for a part especially in a parallel lines situation.
        - Possible refinement: Use Microsoft Excel to store all the lists of destinations. These lists can be accessed by the prototype in real time.

<u>Part</u>

- At the present moment, the prototype is capable of providing up to 99 parts at a time but only one part with routing function facilities is provided.

- Possible refinement: Provide new variables to store all the destinations for each part so that all of them can be accessed by the routing function in Witness.

7.4.5 Summary of opportunities for further refinement

The strengths and weaknesses established indicate some opportunities for further improvement. Weakness factors discussed in the previous section can be used as a guideline to improve the developed prototype since it has potential to be enhanced in the future.

At the moment, the prototype provides four templates for performance measures: long lead time, high WIP, machine utilisation and high scrap or waste. The author did not see this as a weakness for the prototype because all the templates stored in the library are continuously developed. These templates can be increased from time to time. As this prototype is a proof-of-concept tool it confirms that classification of problems through a cladistics technique and template approach can be one of the alternatives available to facilitate model building.

Therefore further refinements or improvements can be carried out in two ways: i) development of the prototype; ii) classification of problems and templates development. Refinements of the developed prototype are driven by the weaknesses discussed in the previous section. Refinements of classification can be performed in several ways: i) enhancing or strengthening the current classification by adding more details (information) in order to establish a more robust and solid understanding about problems and their evolution, especially in assembly lines; ii) expanding the scope of classification to other layouts such as cellular manufacturing, job shop, etc. A good classification is essential to produce good templates or modules. These two factors are very useful in prototype enhancement and building up a greater understanding regarding the evolution of typical problems in manufacturing systems.

7.5 Chapter summary

This chapter focuses on the validation and evaluation of the developed prototype based on classification of problems using a cladistics technique and template approach. The validation and evaluation illustrate the benefits of the prototype, particularly with regard to its ease-of-use and to rapidly build a simulation model.

The evaluation and feedback forms helped to gain a wider picture of users' understanding of how well the new method of classification of problems and template approach through the development of proof-of-concept prototype was accepted among the participants. Positive feedbacks received indicate that this new method has its own advantages that will benefit the simulation modelling area. In addition, negative feedbacks received will be used for further refinement or improvement in the future.

8 DISCUSSION AND CONCLUSION

This research has established a new method to rapidly build a simulation model using an evolutionary analysis technique called a cladistics and template approach. In addition, a proof-of-concept prototype which is called a "rapid model generator" has been developed to visualise the new method investigated. This chapter summarises the whole research including research findings and discussion, contributions, future research opportunities and conclusions. This chapter is organised as follows: Section 8.1 provides an overview of the research aim, objectives and programme. Section 8.2 addresses the research findings. Section 8.3 presents the research findings compared to research objectives. Section 8.4 focuses on research contributions. Section 8.5 identifies the limitations of the research. Section 8.6 focuses on the recommendations for future works. Finally, Section 8.7 provides the concluding remarks of this research.

8.1 Overview of research aim, objectives and programme

The aim of the research is described as follows:

"*To investigate a new method to facilitate model building in order to reduce the model development time using a cladistics technique and template approach.*"

To achieve the above aim, the following research objectives were identified.

- To establish an understanding of typical problems in manufacturing systems (especially in assembly lines).
- To apply a cladistics technique to problems (sample data) established for classification and evolutionary analysis.
- To develop a proof-of-concept prototype which can rapidly build a simulation model based on a template and reusable elements (modules) approach.

A four stage structured programme, as shown in Chapter 3, has been developed in order to achieve the objectives stated above:

- Stage 1: Collection of typical problems in assembly lines (Chapter 4)
- Stage 2: Cladistics technique and classification (Chapter 5)
- Stage 3: Prototype development (Chapter 6)
- Stage 4: Testing and validation (Chapter 7)

In addition, Chapter 7 discusses the validation process as proof that the new method, which is established based on the classification of problems using a cladistics technique and template approach, is capable of reducing model development time.

8.2 Research findings

The following is a summary of the research findings.

1. In the context of model building, simulation tools alone appear to be incapable of facilitating the model building process and reducing model development time, due to the complexity of problems that need support, skills and knowledge in using simulation tools, as well as experience in model building.

2. This research has found that the simulation process not only requires physical elements in model building but also requires specific elements and logics for performance measures in order to monitor established problems.

3. This research has addressed some of the common problems found in assembly lines, by providing the relationships and evolution between the related problems through a tree structure diagram called a cladogram, which is based on a cladistics technique. The cladogram will benefit modellers, developers and researchers in identifying the specific elements required for simulation.

4. The research methodology established can be used as a guideline for other researchers to enhance the current methodology used. The benefits of adopting the methodology (combination of classification of problems and template approach) include reduced model development time, reduced cost of training or cost of simulation tools, and an improved understanding of evolution of problems with their related performance measures and simulation elements.

8.3 Research findings compared to research objectives

The following sections discuss the comparison between the research findings and the research objectives.

8.3.1 Objective 1: To establish an understanding of typical problems in assembly lines

Common problems in assembly lines were collected through a literature review as sample data. Even though the problems have been collected solely from the literature review, they are more than enough to represent the common problems established in assembly lines. The principle deliverables of this objective are a compilation of problems and characteristics in assembly lines, initial classification of problems, typical physical elements and performance measures available, material flows, routing logic, etc. This compilation is very useful as a reference and as a foundation upon which the next objective will be based. The key findings show that the collected problems have covered quite a number of common problems established in assembly lines. Some of them have been used for the development of the proof-of-concept prototype in this research.

8.3.2 Objective 2: To apply a cladistics technique for the classification of problems

The cladistics technique has been used to produce the final classification of problems in assembly lines. The main deliverable is a cladogram, a tree structured diagram that represents the history of evolution of a group of common problems in assembly lines. A matrix table consisting of problems and their characteristics were developed in order to produce a cladogram. Statistical analysis has been implemented to ensure that the sample data fit the cladogram. The statistical analysis results show that 73% of the characteristics and problems fit each other with fewer conflicts in order to produce the most parsimonious tree, the established cladogram is acceptable and the quality is good.

8.3.3 Objective 3: To develop a proof-of-concept prototype

In order to evaluate the effectiveness of the proposed conceptual solutions in facilitating and rapidly building a simulation model, a prototype of a rapid model generator has been developed in this research. As it is intended to be a proof-of-concept, the prototype has been developed using a commercially available discrete-event simulation tool called Witness. The engine of the prototype was developed using Visual Basic and linked to the Witness simulation tool. The prototype consists of a graphical user interface that interacts with users and displays the output in the Witness simulation tool. The first action in the development stage was to identify the relevant elements required for templates and library development, from which collections of physical and performance measure elements will be retrieved and customised further to suit the need of the modellers, based on established problems. The prototype provides the physical elements, performance measure elements and logics for simulation. A simulation model is assembled by retrieving elements from the library. The model developed consists of elements in the form of templates and it is built automatically based on user requirement. Users can change the simulation parameters and experiments can be designed accordingly. It is important to note that templates can be developed in any simulation tool and the final deliverables may not be using Witness.

In the next stage, the proof-of-concept prototype is validated and tested by the walk-through (expert judgement) method, where users were required to perform some exercises using the developed prototype. The purpose of the validation process is to identify to what extent the prototype can help users in model building. The confirmatory study will be carried out through the feedback forms provided in order to capture users' perceptions of ease-of-use, user friendliness and usefulness of the prototype.

8.4 Research contributions

This research has delivered a number of contributions in the field of model building and simulation modelling. The research contributions are listed below:

8.4.1 Contributions in establishing a thorough understanding of typical problems in manufacturing systems (assembly line)

A thorough understanding of problems, especially in assembly lines, has been carried out by reviewing some publications as sample data for classification development. The relevant information, especially the relevant characteristics for each problem, has been extracted from the reviewed papers. This process was not as easy as expected because some problems may share one or more characteristics and one problem can be a characteristic of another problem. Such situations (extracting and selecting the relevant information) are crucial because they will affect the cladogram. As a summary, the key findings are very useful in developing the understanding of common problems in manufacturing activities, especially in assembly lines.

8.4.2 New technique and method to rapidly build a simulation model

The aim of this research is to investigate a new method to rapidly build a simulation model. Two main contributions have been established: i) a cladistics technique is used for classification and evolutionary analysis; ii) a template approach is used to reduce the model development time. Firstly, the cladistics technique generates a classification in the form of a phylogenetic tree which is called a cladogram. This cladogram shows the evolution of problems with the characteristics involved. Apart from that, a cladogram provides useful and helpful information to modellers in identifying the relevant physical and performance measure elements required for simulation modelling. Secondly, the elements required for simulation modelling are stored in a library in the form of a module or template. These templates can be accessed by the proof-of-concept prototype very easily and quickly. The cladogram and templates developed are not the final key findings, however. Since the problems and their characteristics are evolved over time, the cladogram will be continuously developed. The cladogram may change subject to new problems and characteristics; once it is updated, the library of simulation templates will also be updated. The library is a repository for all templates that can be changed, added or deleted over time, based on the changes to the cladogram. As a summary, this research provides a substantial advancement of knowledge by: i) exploring the use of cladistics and evolutionary analysis as a basis of classification for assembly line systems and problems being addressed using simulation; ii) investigating a new method to rapidly build a simulation model for assembly lines and the problems to be addressed.

8.4.3 New development of a proof-of-concept prototype

The main contribution of the developed prototype is shifting the concept of “model building” towards “model assembling”, where the elements can be retrieved from a ready to use library and the complete model can be generated automatically in order to speed up model building. The prototype has been developed based on the classification of established problems. The prototype was designed to be user friendly and easy to use in order to facilitate users to develop a simulation model which consists of physical elements such as the performance measure elements for problems. The results from the testing and validation in Chapter 7 show that development of the proof-of-concept prototype based on the classification of problems using a cladistics technique and template approach can help users in model building and reduce model development time.

8.4.4 Summary of contributions to knowledge

Table 8-1 shows the main issues of model building being addressed in the thesis.

Table 8-1 Summary of contributions to knowledge

Contribution to knowledge	Achievement to date
Establishing a thorough understanding of typical problems in manufacturing systems (assembly lines)	Common problems and their characteristics have been extracted and collected from the literature review
New technique and method to rapidly build a simulation model	Combination of cladistics technique and template approach. Templates have been developed based on classification of problems established using the cladistics technique.
	Evolution of problems and elements required for simulation modelling can be traced and identified based on an established cladogram.
New development of proof-of-concept prototype	Based on the testing and validation results, it is proved that the developed prototype is capable of tackling some of the model building issues addressed in Chapter 2 as listed below: • Model building is time-consuming and has high cost activities • Model building requires a good knowledge of programming and modelling skills • Model building is a complex task • Simulation tools are difficult to use

8.5 Limitations of the research

This section discusses the limitations of this research as they can be the key points for future enhancement.

8.5.1 Scope of problems (sample data)

This research focuses on assembly lines because the scope of manufacturing systems itself is huge and covers many problems. Some of the problems extracted are very common in manufacturing activities and could be found in other layouts or systems, and they might share similarities in terms of templates used for simulation. Since assembly lines are complex and as time has been a limiting factor for this research, sample data collected from the reviewed papers cannot cover all the problems involved in assembly line systems. Future enhancement can be carried out in order to provide more robust data for the purpose of classification development.

8.5.2 Cladistics and parsimony method

The cladistics technique and parsimony method has been used to establish the classification in the form of a cladogram. The parsimony method is based on the assumption that the best tree is a tree with the fewest total number of changes of character state from 1 to 0 or vice versa. Since the data collected are based on characteristics (not protein data such as DNA or nucleic acid sequence), the parsimony method is the best option available to classified problems. In addition, the parsimony method has been recognised in the literature based on previous publications, especially in the manufacturing area.

8.5.3 Templates

Templates or modules that have been developed only cover a few problems: i) long lead time; ii) high WIP; iii) bottleneck; iv) high scrap/waste. The number of templates in the library can be increased at any time because they are continuously developed based on the established cladogram. Since Cranfield University has a licence for one of the simulation software, i.e. Witness, all the templates have been developed using this software. It must be borne in mind that these templates can be developed in any software and the final deliverables may not be using Witness.

8.5.4 Proof-of-concept prototype

In the context of this prototype, the user still needs to detail the element manually by typing some logics into that element's properties in Witness, especially when working with performance measures. This step should be automated unless the user has decided to customise some functions in the element or is detailing the element on their own, as typing can be quite tedious and time-consuming. Full details of this issue can be found in Section 7.4.4.

8.6 Recommendations for future works

Since simulation modelling in manufacturing systems, especially assembly lines, is complex, the established results may not be close to reality but they are capable of providing ways of obtaining the early visibility of problems faced in manufacturing activities. Therefore appropriate measures can be carried out to reduce or monitor the established problems.

Based on the limitations stated in the previous section and summary of opportunities for further refinement discussed in Section 7.4 for the developed prototype, improvements can be carried out to produce a more robust classification of problems and prototype development. These include: i) refining the logic in controlling the routing of parts; ii) enhancing the templates with more complex logic; iii) improving the way to store the destinations for the route of a part; iv) refining the details of the established classification; v) expanding the scope of classification to other layouts such as cellular manufacturing, job shop, etc.

8.7 Concluding remarks

This chapter has addressed the aim of this research associated with the objectives and research programme, and major contributions to knowledge.

Strengths, weaknesses and limitations of the research have been identified and recommendations for future works are presented for more improvements. It is hoped that knowledge gained from this research will improve the simulation and model building processes of the future.

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APPENDICES

Appendix A Data type

Source: Lanner Group (2005)

Symbol	Data type
(R)	Real
(I)	Integer
(S)	String
(N)	Name

Appendix B Machine states that the ISTATE, PUTIL and SUTIL use

Source: Lanner Group (2005)

State number	State	Colour
0	Off-shift	White
1	Waiting for parts	Yellow
2	Busy	Green
3	Blocked	Magenta
4	Setting up	Cyan
5	Being repaired	Red
6	Waiting for labour to cycle	Blue
7	Waiting for labour to set up	Cyan
8	Waiting for labour to repair	Red
9	Filling	Green
10	Emptying	Green
14	Waiting for parts to arrive at machine using path	Yellow
15	Waiting for labour for cycle to arrive using path	Blue
16	Waiting for labour for setup to arrive using path	Cyan
17	Waiting for labour to arrive at machine to remove parts	Magenta

Appendix C Evaluation forms

Evaluation forms

Rapid Model Generator for Manufacturing Simulation

Aim: To investigate a new method to rapidly build simulation model based on classification of problems using cladistics technique and template approach.

This exercise is part of the study in developing a prototype referred to as “Rapid Model Generator” in simulation modelling. Your participation in this study will help us improve the design of the prototype.

We would appreciate if you could give us your true opinion and suggestions about the prototype. Please note that we are evaluating the prototype, NOT your performance in using the software. The intention is to measure to what extent the prototype can help the user build the model.

Mode A: Building a model manually

Exercise 1: Building, linking and running a model

Please build a model as shown on Figure C-1. Linking all the elements and run the model. A part is delivered to Machine1 and other elements as shown below.

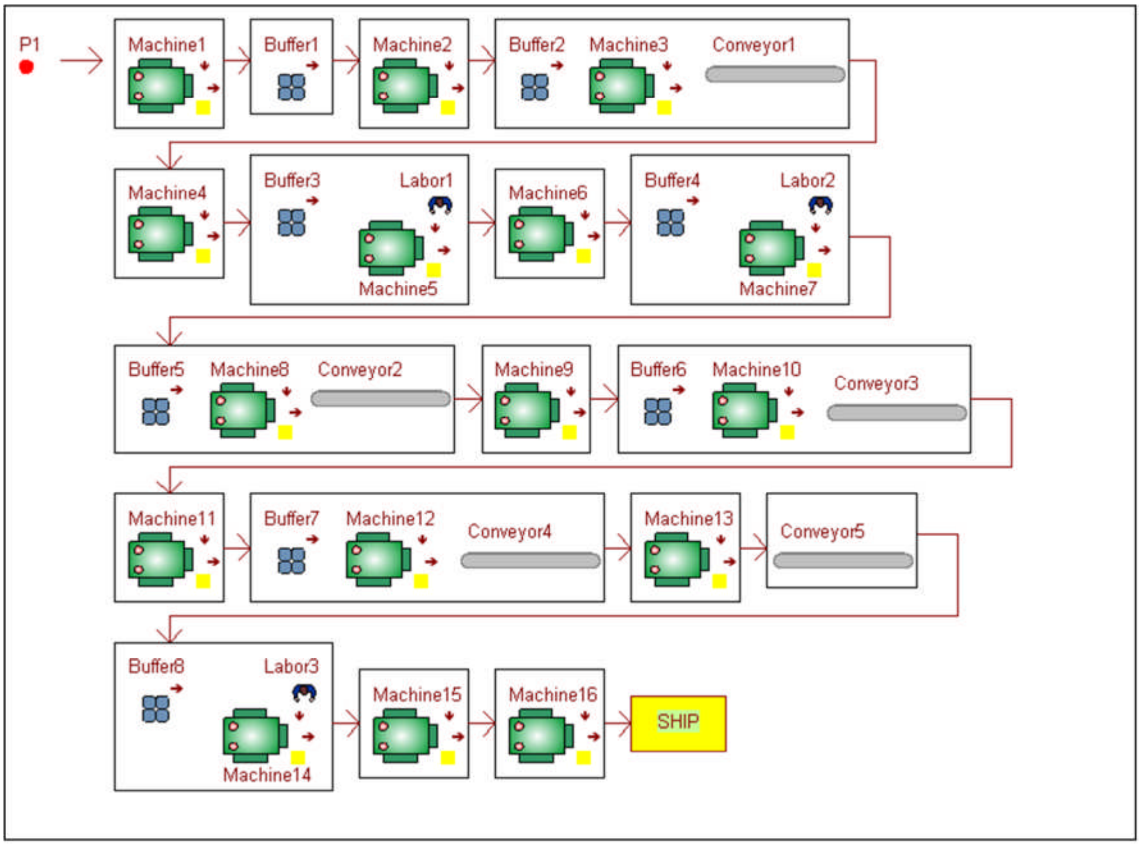

Figure C-1 Layout

Table C- 1 Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

<u>Evaluation: Exercise 1</u>

	Difficult					Easy
Exercise 1	1	2	3	4	5	6

Exercise 2: Changing the routing

Exercise 2(a): Amend the previous model with the following layout (Figure C-2). Link the elements and run the model.

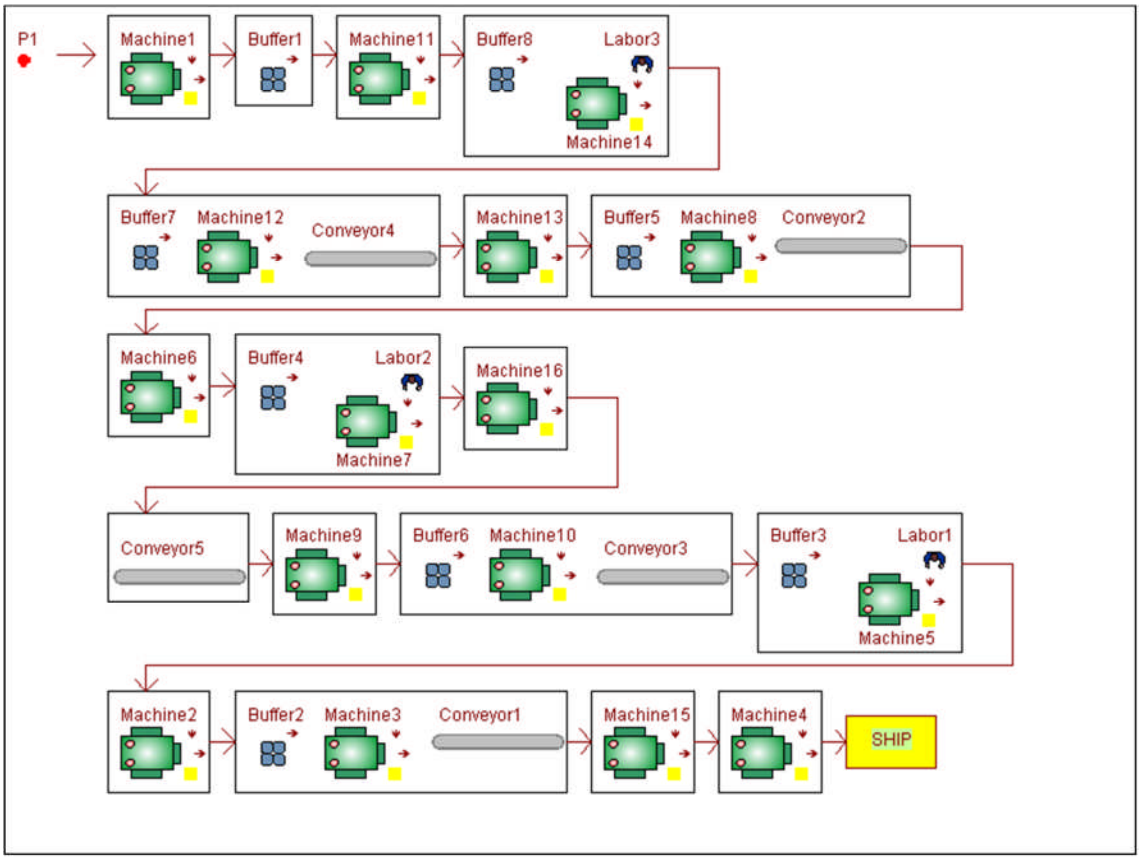

Figure C-2 New layout

Exercise 2(b): Make a new link (route) for the part. The part needs to bypass elements circled as shown in Figure C-3.

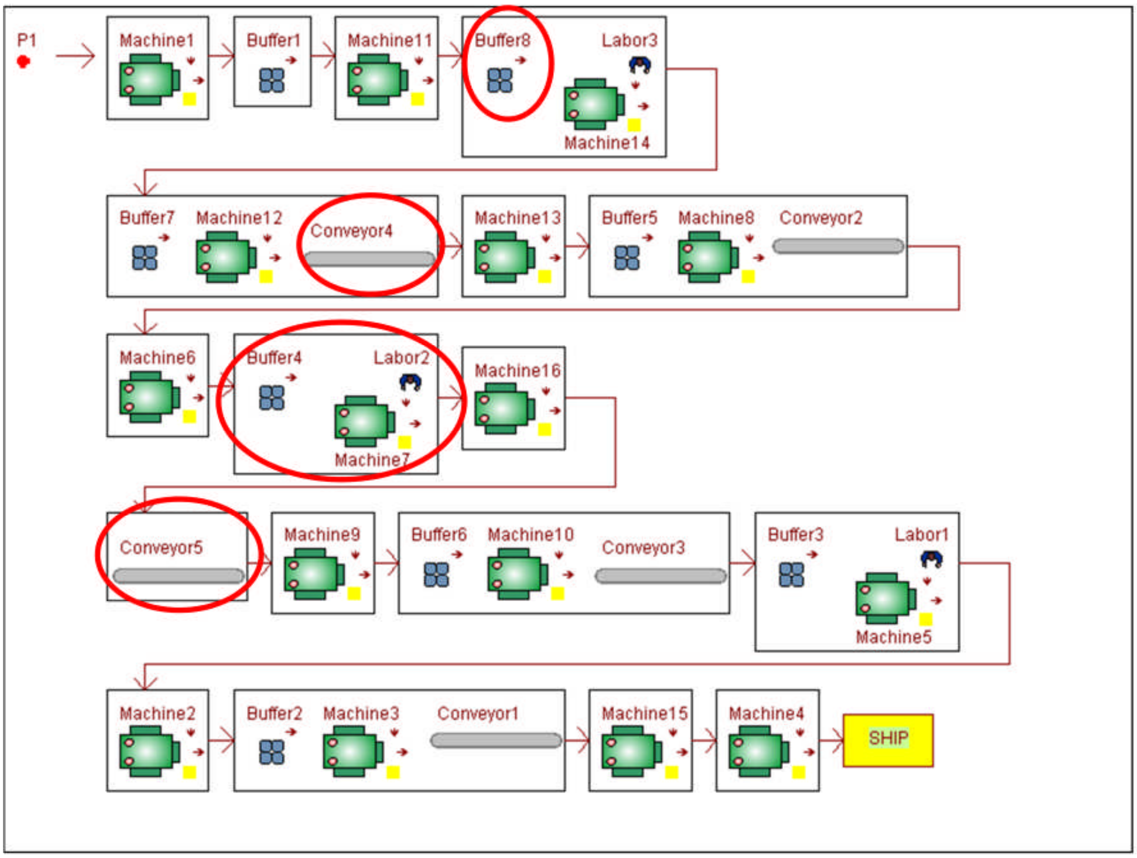

Figure C-3 Changing the routing

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure C- 4.

Exercise 3a(i)

- In order to include the breakdown in “Machine11”, it is necessary to specify that breakdown will occur in the element details as shown in Figure C- 5.

- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use time series to plot the number of WIP over time).
- Find out the average of machine utilisation (“Machine11”) (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3a(ii)

- Delete the breakdown details in “Machine11”.
- In order to include the breakdown in “Machine15”, it is necessary to specify that breakdown will occur in the element details as shown in Figure C- 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use time series to plot the number of WIP over time).
- Find out the average of machine utilisation (“Machine15”) (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

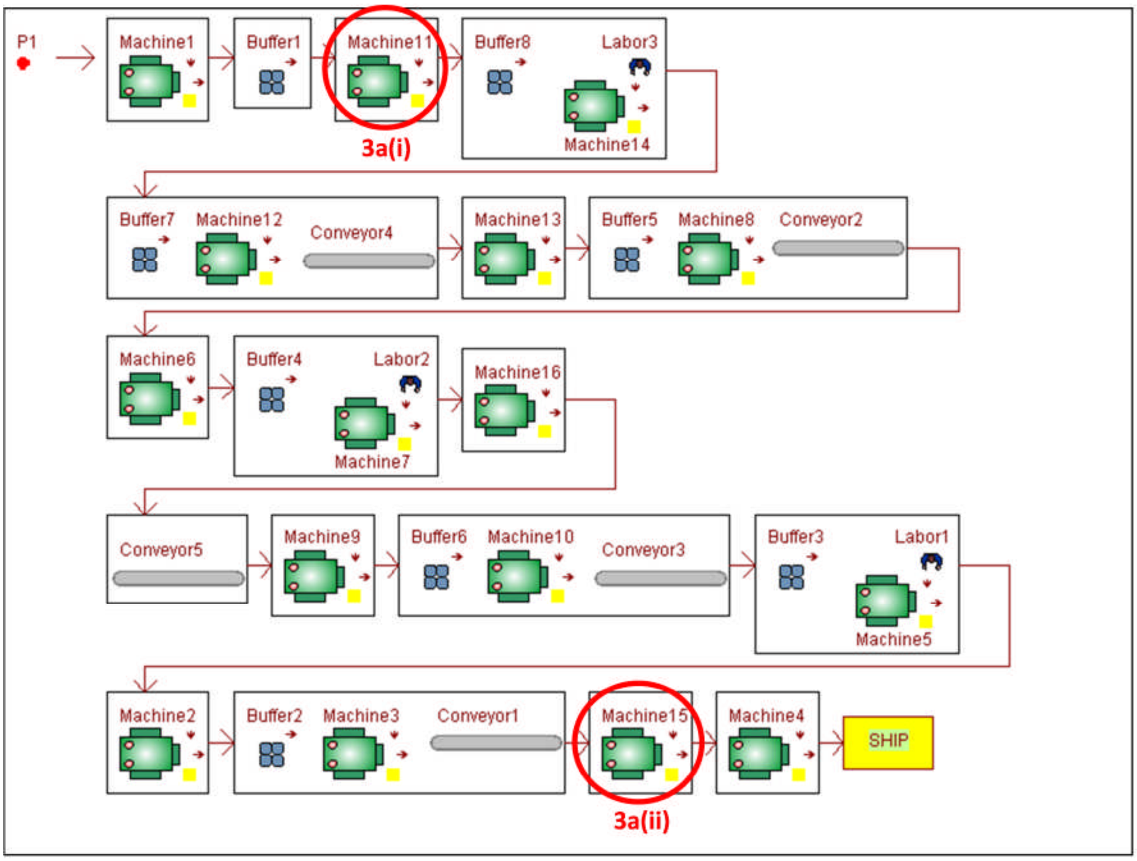

Figure C- 4 Exercise 3a

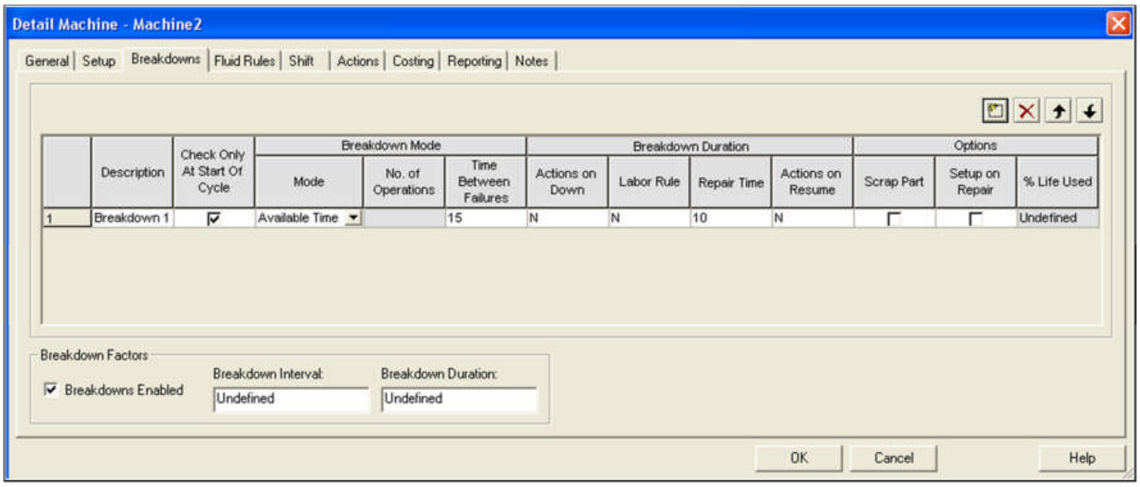

Figure C- 5 Data for machines breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

Evaluation: Exercise 3(a)

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

Exercise 3b: Comparing the effect of machine reliability (breakdown) for Machine16 as shown in Figure C- 6 based on two conditions:

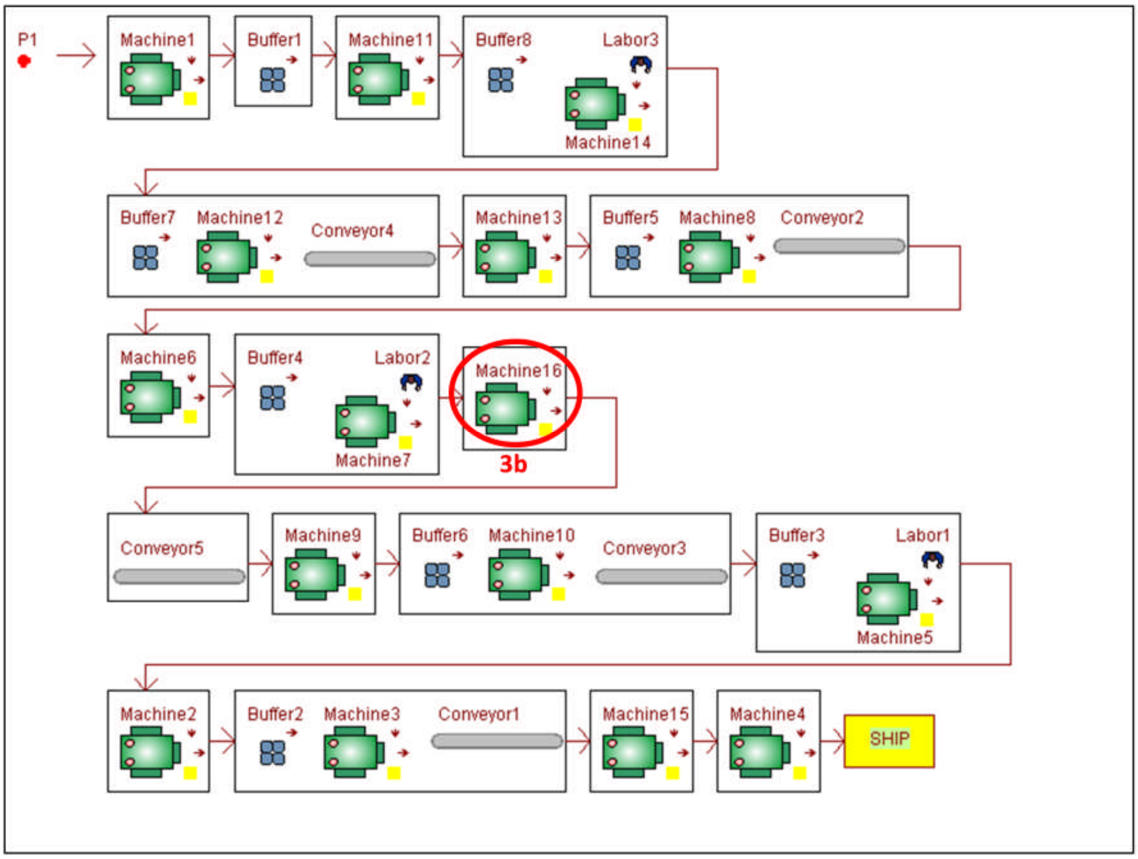

Figure C- 6 Exercise 3b

Table C- 2 Data for Exercise 3b

i. breakdown is often (short MTBF[1]) but repair time is quick (short MTTF[2])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

Exercise 3b(i)

- In order to include the breakdown in "Machine16", it is necessary to specify that breakdown will occur in the element details as shown in Table C- 2 (i).
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

[1] MTBF: Mean time between failures
[2] MTTF: Mean time to failure

Exercise 3b(ii)

- Change the details of breakdown as shown in Table C- 2 (ii).
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

Mode B: Building the model using prototype

Please follow the guidelines and instructions provided for each exercise.

Exercise 1: Building, linking and running a model (Normal Modelling)

Please build a model as shown on Figure C- 7. Linking all the elements and run the model. A part is delivered to SM1 and other elements as shown below.

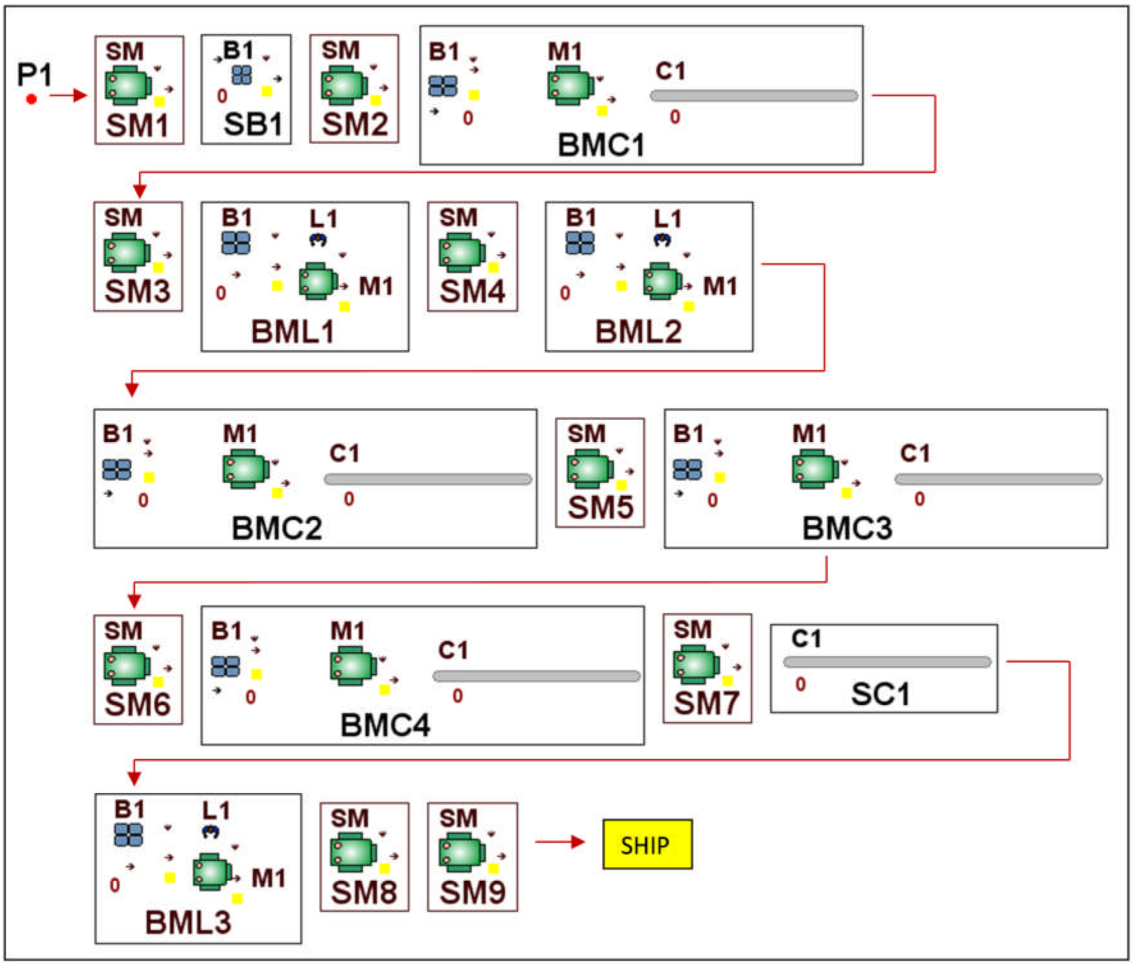

Figure C- 7 Layout

Table C- 3 Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Step 1:

- Please select “Assembly line” from the list of layouts as shown in Figure C- 8.
- Click “Next” button

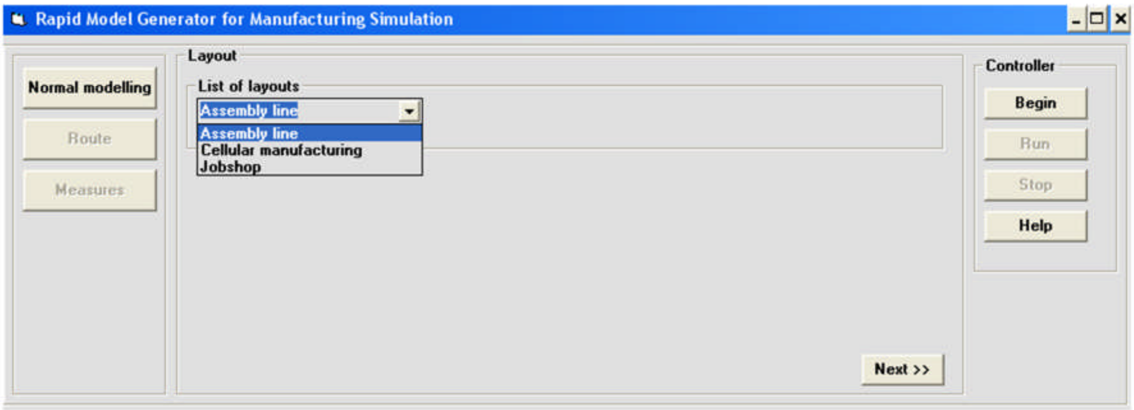

Figure C- 8 List of layout

Step 2:

- Please select the modules and quantity of each module as shown in Figure C- 9 and Table C- 4.
- Select the module and quantity required, then click “Add” button. Repeat this step for each module.
- When all modules have been selected, click “Begin” button, then “Run” button. Now, all the modules are shown in the screen.
- Click “Stop” button.
- Position each module based on layout required as shown in Figure C- 7. Click the module, drag and drop. Then, click “Next” button to link the elements (route for the part).

Table C- 4 Data for modules and its quantity

Module	Quantity
P (Part)	1
SM (Single machine)	9
SB (Single buffer)	1
SC (Single conveyor)	1
BMC (Buffer machine conveyor)	4
BML (Buffer machine labour)	3

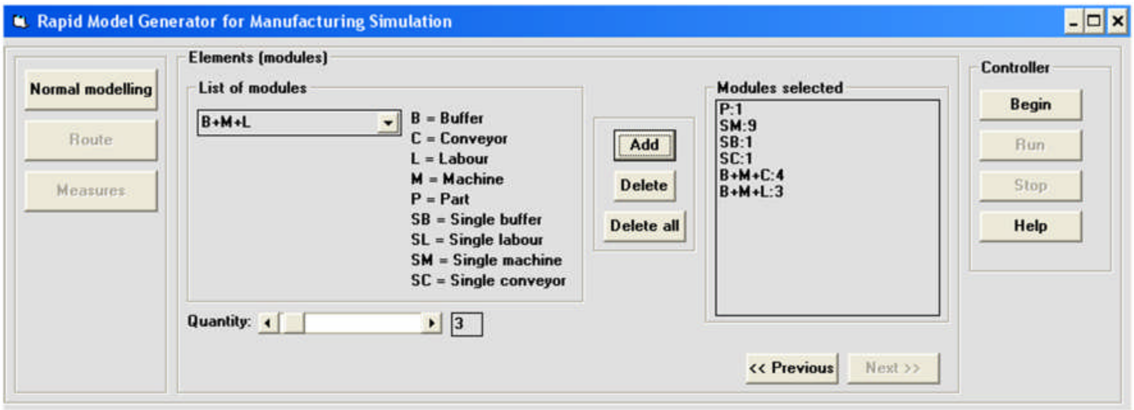

Figure C- 9 Modules and quantity

Step 3:

- Please add route for the part as shown in Figure C- 10.
- Select the first destination and click “Add” button. Repeat this step until the last destination.
- Click “Next” button and “Run” button.
- To stop the process, click “Stop” button
- Now, run the simulation model with run time at 480 unit time. Click the “Start RunAt” option on the “Execute Action Bar” at the bottom of the Witness screen. In the text box, enter the time as 480. Switch OFF the walk speed by clicking the “Walk ON/OFF” button. Then click “Run” button.
- To start again the simulation process at time 0, click “Begin” button on the prototype, then click “Run” button on the “Execute Action Bar” at the bottom of the Witness screen.

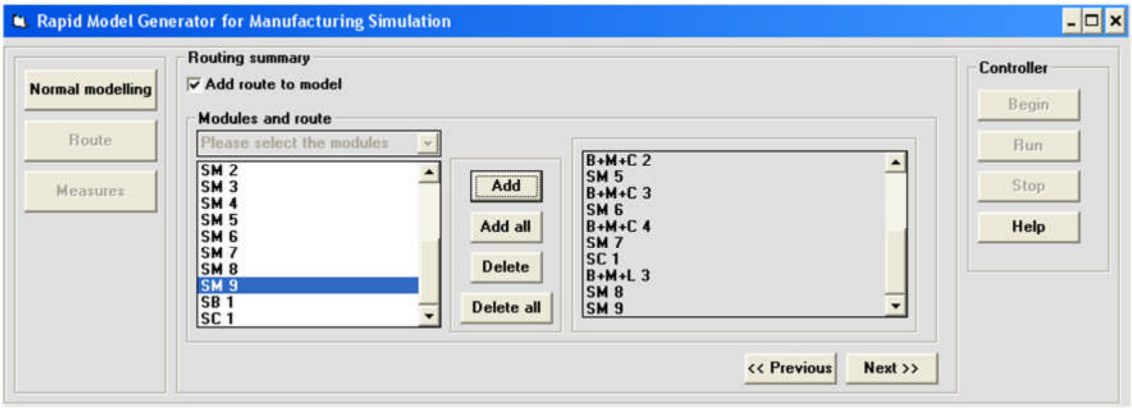

Figure C- 10 Routing

<u>Evaluation: Exercise 1</u>

	Difficult					Easy
Exercise 1	1	2	3	4	5	6

Exercise 2: Changing the routing (Route)

Exercise 2(a): Amend the previous model with the following layout (Figure C-11). Link the modules and run the model.

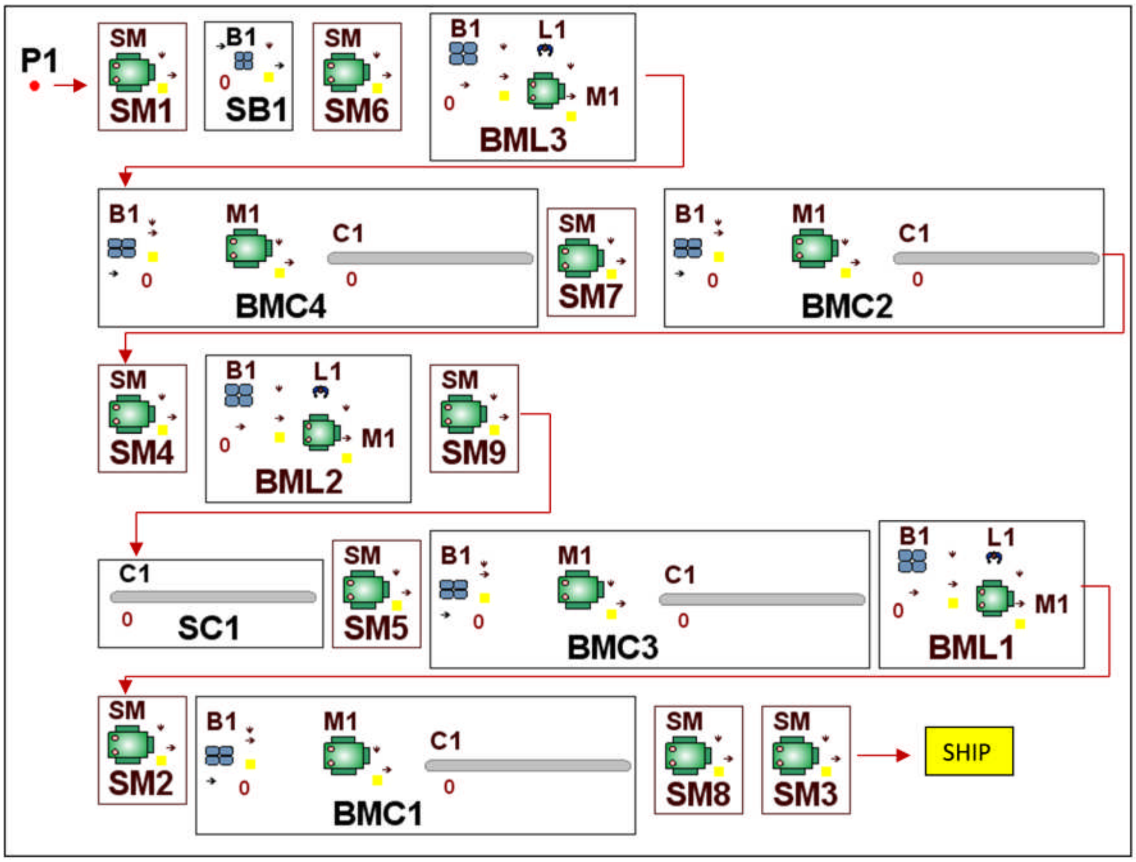

Figure C- 11 New layout

Exercise 2(b): Make a new link (route) for the part. The part needs to bypass elements circled as shown in Figure C- 12.

Step 1:

- Click the “Route” button.
- The current route is shown in left panel. Click “Add all” button and the current route is now available in the right panel (New Route) as shown in Figure C- 13.
- On the “New Route” panel, select the element B1 in the “BML3” module, and click “Delete”. Repeat this step for element C1 in module “BMC4”. Then delete all elements in module “BML2” and module “SC1”. Then click “Begin” button and “Run” button.

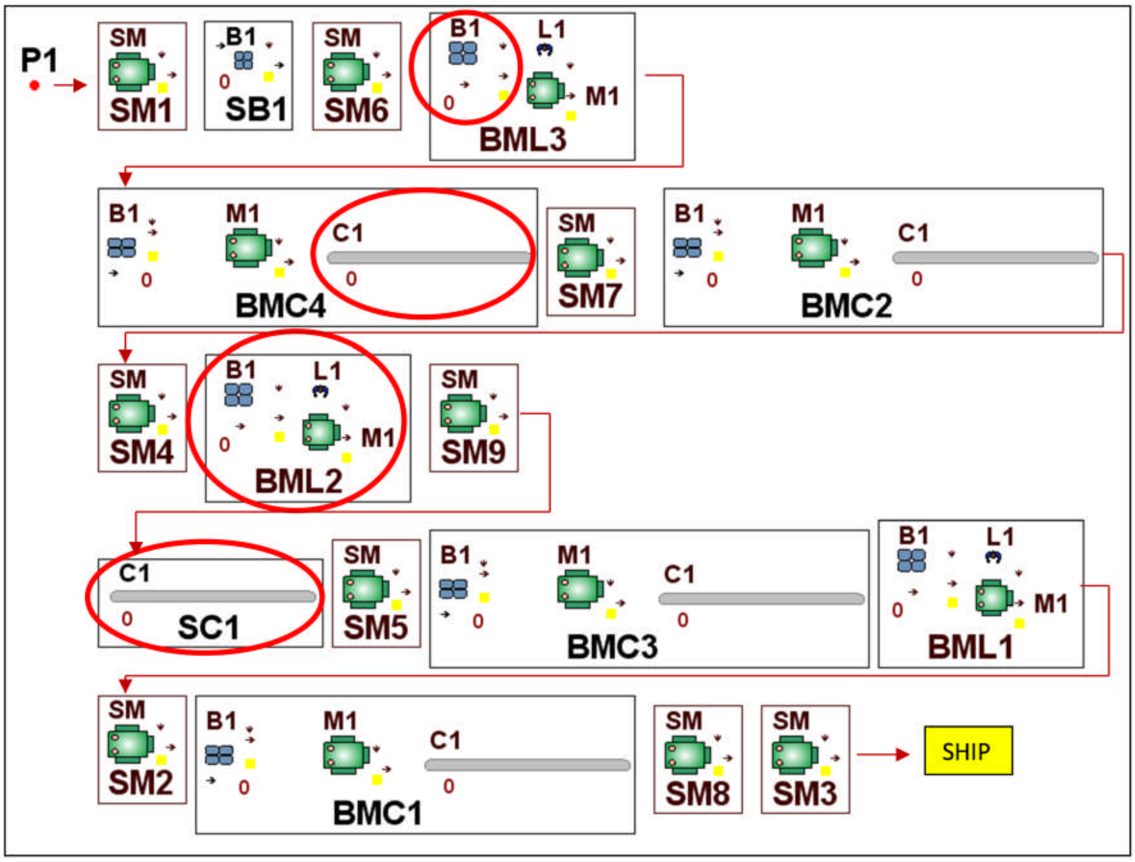

Figure C- 12 Changing the route

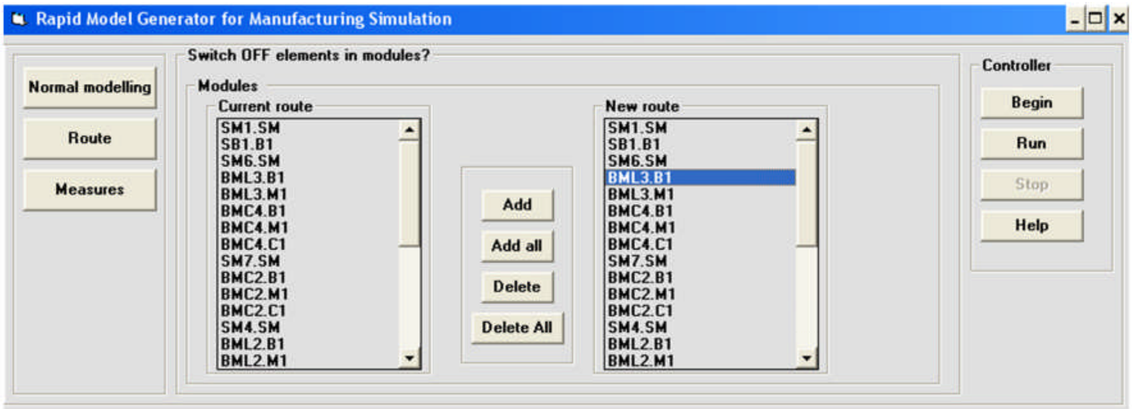

Figure C- 13 Switching ON/OFF elements in modules

<u>Evaluation: Exercise 2</u>

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures (Measures)

General guidelines

To measure the lead time:

- Click the "Measures" button.
- Select "Long lead time" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button as shown in Figure C- 14.
- Now, click "Stop" button. A histogram is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the lead time.

(Note: Please use histogram to display the average of lead time).

To measure the WIP:

- Select "High WIP" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button.
- Now, click "Stop" button. A time series is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the WIP.

(Note: Please use time series to plot the number of WIP over time)

To detect the bottleneck:

- Select "Bottleneck" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button
- Now, click "Stop" button. Three pie charts are provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the machine utilisation.

(Note: Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

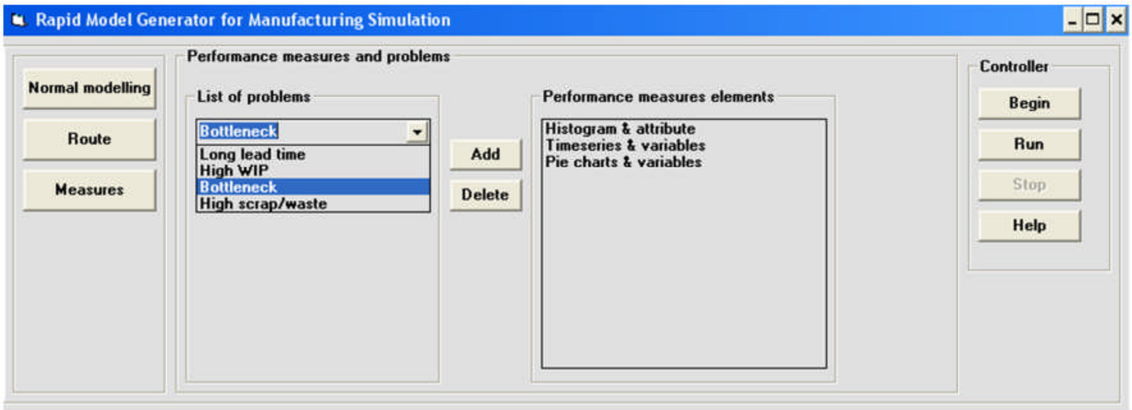

Figure C- 14 Measures

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure C- 15.

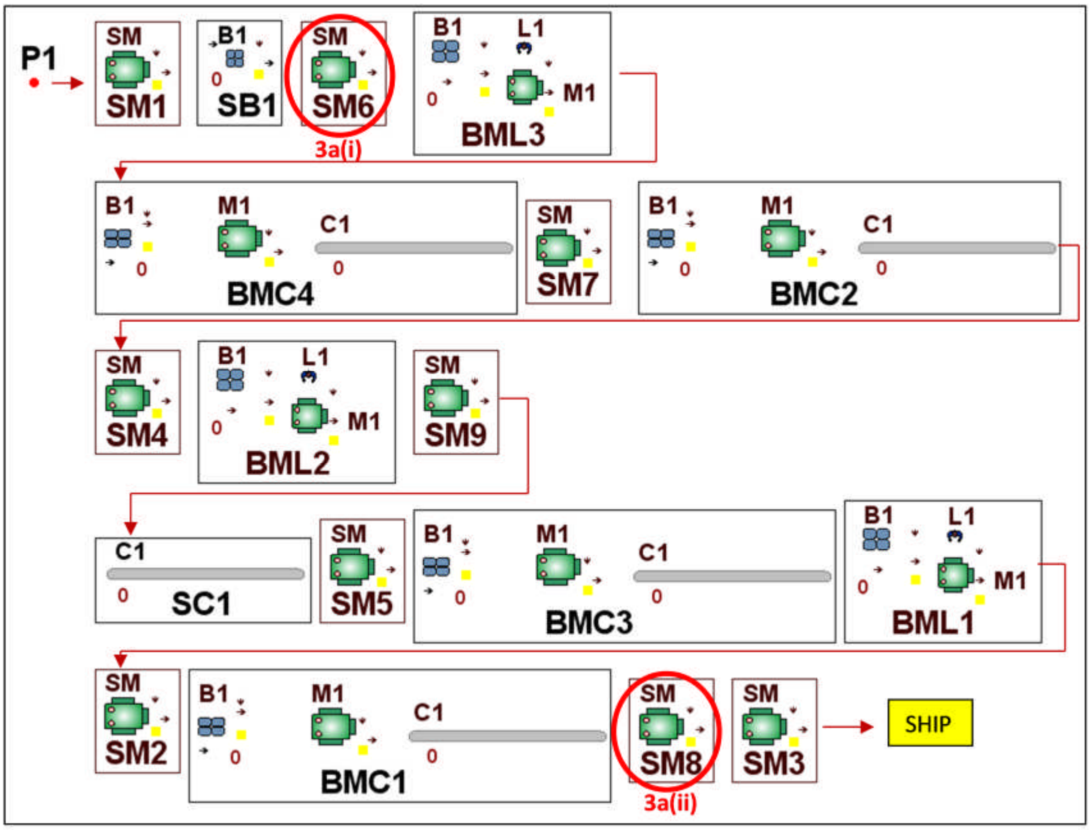

Figure C- 15 Exercise 3a

In order to include the breakdown in both machines, it is necessary to specify that breakdown will occur in the element (machine) details as shown in Figure C- 16.

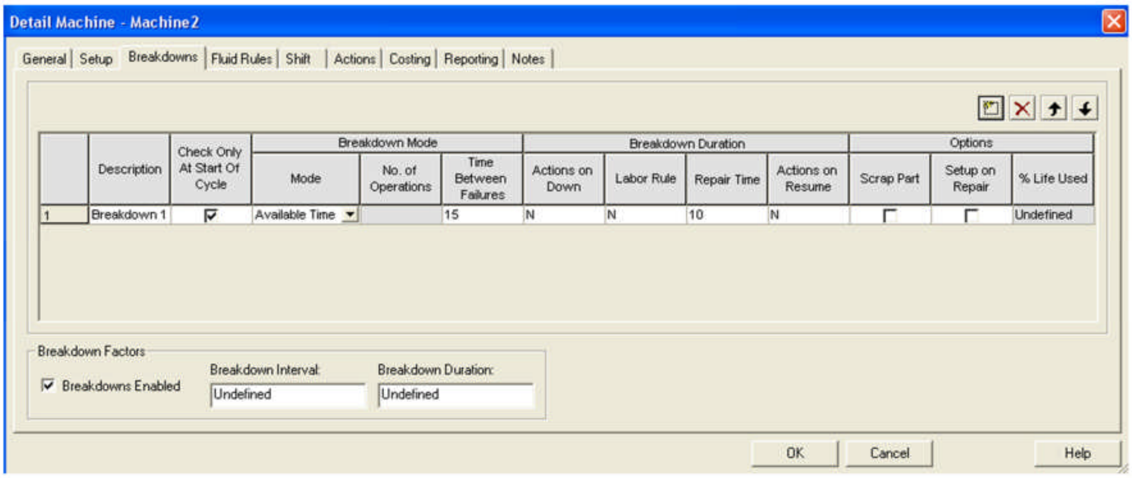

Figure C- 16 Data for machine breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

<u>Evaluation: Exercise 3(a)</u>

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

Exercise 3b: Comparing the effect of machine reliability (breakdown) for SM9 as shown in Figure C- 17 based on two conditions:

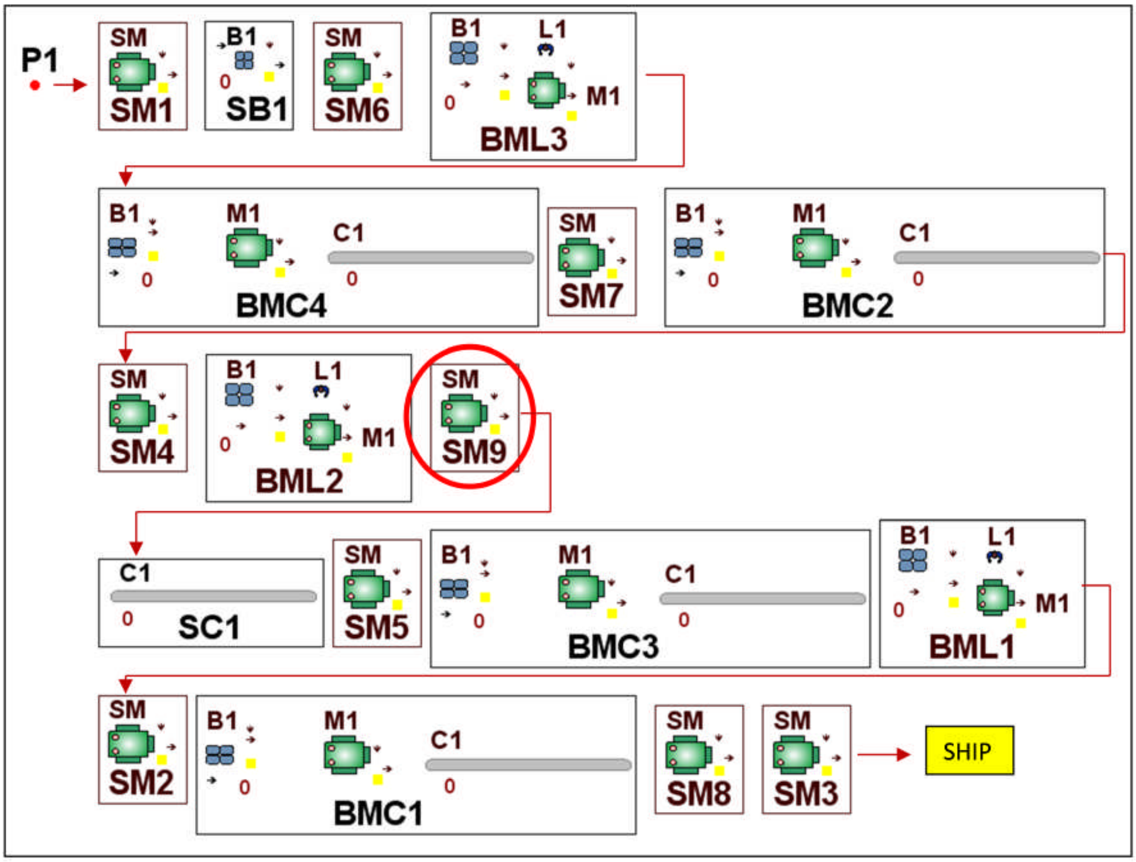

Figure C- 17 Exercise 3b

i. breakdown is often (short MTBF[3]) but repair time is quick (short MTTF[4])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[3] MTBF: Mean time between failure
[4] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

Appendix D Feedback forms

The purpose of these questions is to measure to what extent this prototype can help the user to build the model. Please circle the number between 1 – 6, 1 being Strongly Disagree and 6 being Strongly Agree.

1. **User experience**

How long have you been involved in simulation and model building area?

Never	0 – 6 month	7 – 12 month	More than 12 month	No longer

2. **Usage of Witness software (please tick)**

During lectures only	
During group project	
During thesis project	
Before I came to Cranfield University	

3. **Ease of use**

	Strongly Disagree					Strongly Agree
The prototype is easy to use	1	2	3	4	5	6
The instructions are easy to read and understandable	1	2	3	4	5	6

4. **Usefulness**

	Strongly Disagree					Strongly Agree
The prototype will help me in model building	1	2	3	4	5	6
The prototype will help reduce time for model building	1	2	3	4	5	6
I can create the physical elements easily and faster	1	2	3	4	5	6
I can link the elements and run	1	2	3	4	5	6

the model easily						
I can switch ON/OFF any elements, link them again and run the model easily	1	2	3	4	5	6
I can easily measure the performance of the system (throughput rate, WIP, etc.)	1	2	3	4	5	6
All the elements provided for the performance measures are useful	1	2	3	4	5	6
The prototype has a lot of potential in improving model building	1	2	3	4	5	6
I will recommend this prototype to my colleagues	1	2	3	4	5	6

5. <u>Visual appearance</u>

	Strongly Disagree					Strongly Agree
The prototype displays visually pleasing design	1	2	3	4	5	6
Graphics and colour detract from actual content	1	2	3	4	5	6
The icons of the elements are easy to understand	1	2	3	4	5	6

6. <u>Comments/suggestions</u>

Appendix E Testing and validation results (Participant 1)

Rapid Model Generator for Manufacturing Simulation

Aim: To investigate a new method to rapidly build simulation model based on classification of problems using cladistics technique and template approach.

This exercise is part of the study in developing a prototype referred to as "Rapid Model Generator" in simulation modelling. Your participation in this study will help us improve the design of the prototype.

We would appreciate if you could give us your true opinion and suggestions about the prototype. Please note that we are evaluating the prototype, NOT your performance in using the software. The intention is to measure to what extent the prototype can help the user build the model.

Mode A: Building a model manually

Exercise 1: Building, linking and running a model

Please build a model as shown on Figure 1. Linking all the elements and run the model. A part is delivered to Machine1 and other elements as shown below.

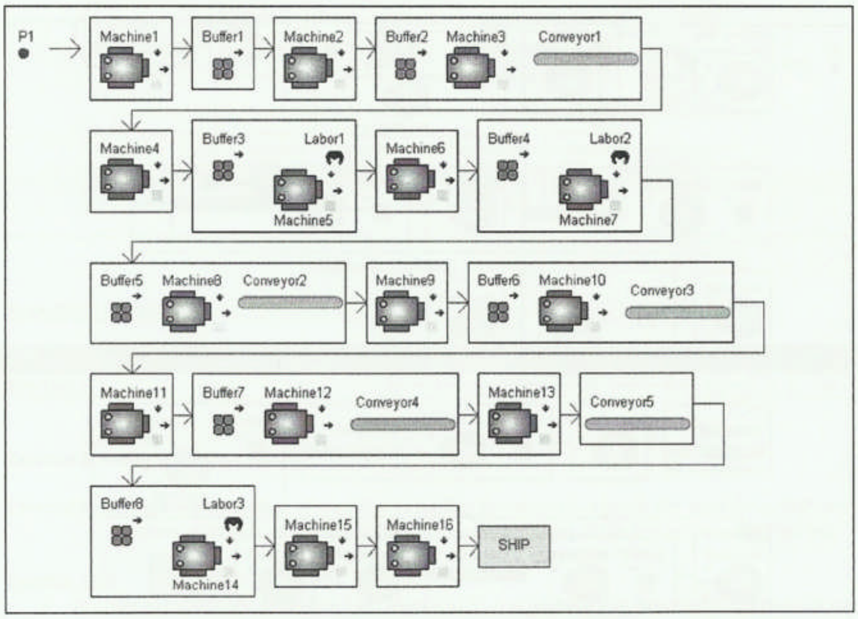

Figure 1: Layout

1

Table 1: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Evaluation: Exercise 1

	Difficult					Easy
Exercise 1	1	2	3	4	5	6

Exercise 2: Changing the routing

Exercise 2(a): Amend the previous model with the following layout (Figure 2). Link the elements and run the model.

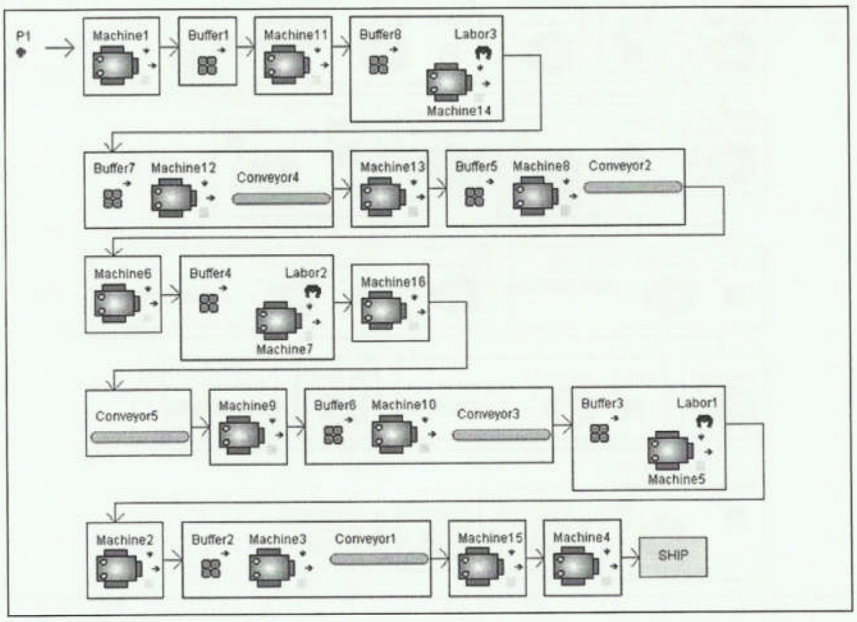

Figure 2: New layout

2

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 3.

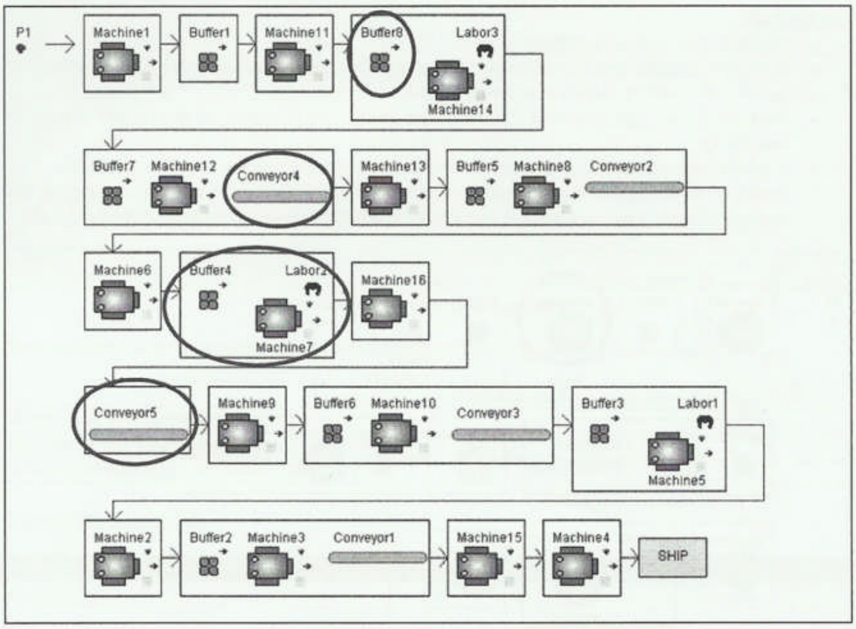

Figure 3: Changing the routing

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 4.

Exercise 3a(i)

Can not be completed.

- In order to include the breakdown in "Machine11", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).

3

- Find out the average of machine utilisation ("Machine11") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3a(ii)

- Delete the breakdown details in "Machine11".
- In order to include the breakdown in "Machine15", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine15") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Can't do this

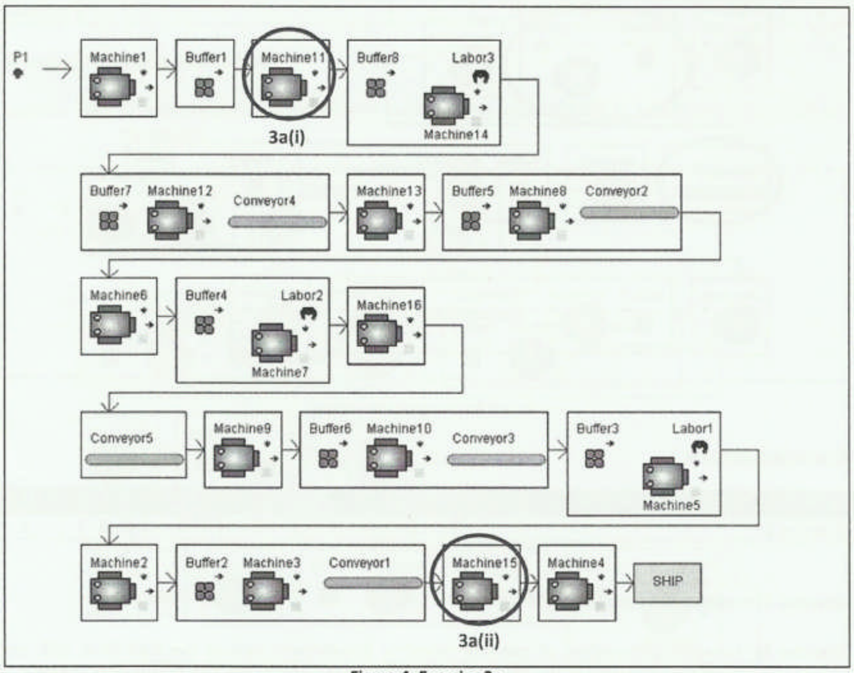

Figure 4: Exercise 3a

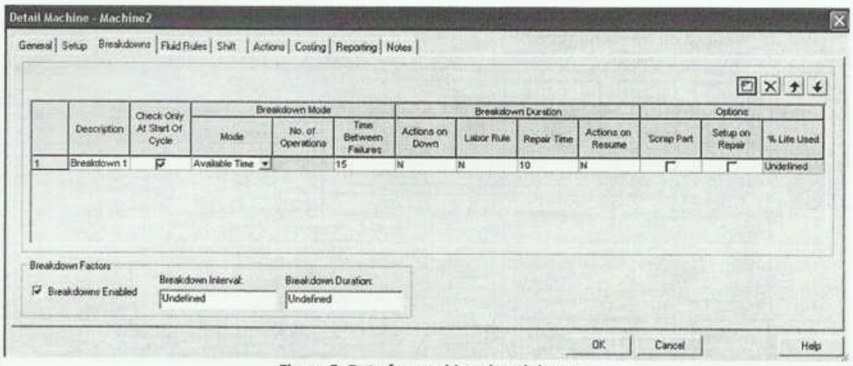

Figure 5: Data for machines breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

Evaluation: Exercise 3(a)

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

Exercise 3b: Comparing the effect of machine reliability (breakdown) for Machine16 as shown in Figure 6 based on two conditions:

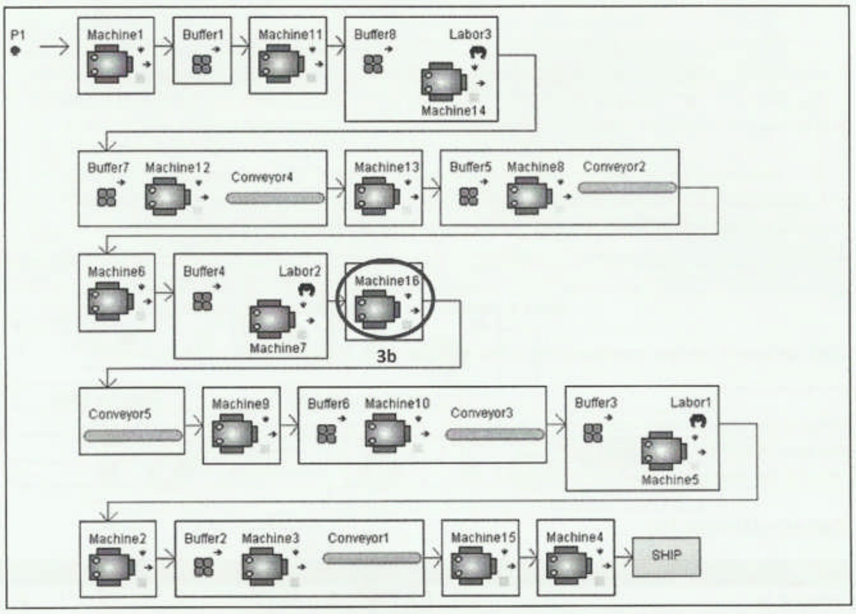

Figure 6: Exercise 3b

Table 2: Data for Exercise 3b

i. breakdown is often (short MTBF[1]) but repair time is quick (short MTTF[2])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[1] MTBF: Mean time between failures

[2] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

Exercise 3b(i)

Can't do this

- In order to include the breakdown in "Machine16", it is necessary to specify that breakdown will occur in the element details as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3b(ii)

- Change the details of breakdown as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

Vinayak
Viswanath

Mode B: Building the model using prototype

Please follow the guidelines and instructions provided for each exercise.

Exercise 1: Building, linking and running a model (Normal Modelling) 6min

Please build a model as shown on Figure 7. Linking all the elements and run the model. A part is delivered to SM1 and other elements as shown below.

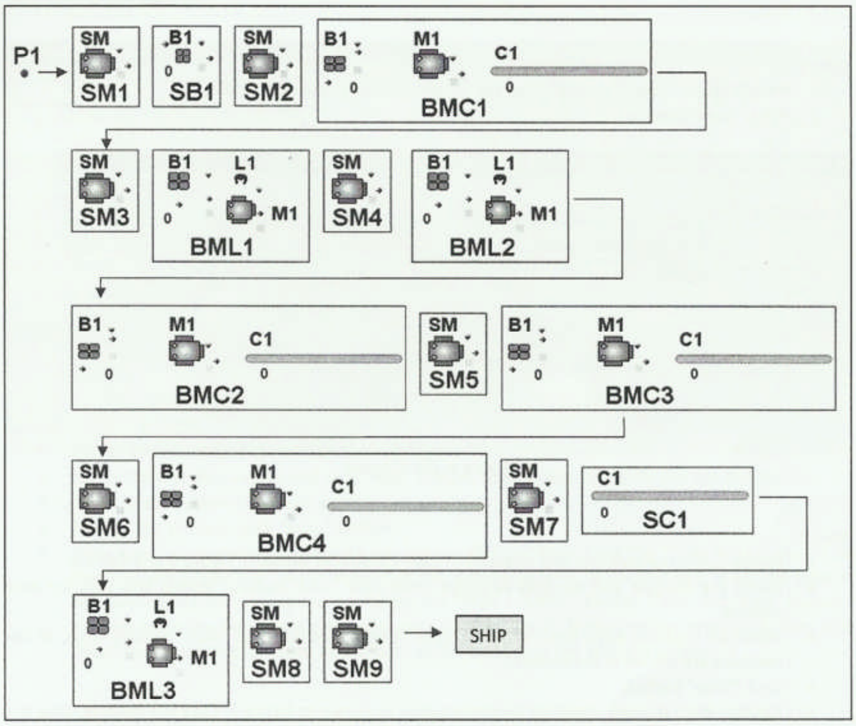

Figure 7: Layout

8

Table 3: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Step 1:

- Please select "Assembly line" from the list of layouts as shown in Figure 8.
- Click "Next" button

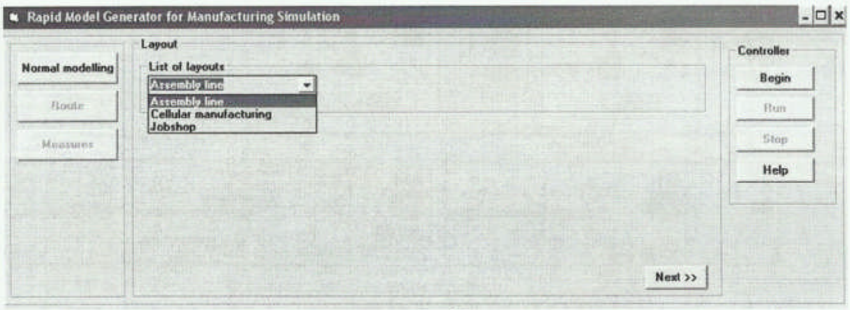

Figure 8: List of layout

Step 2:

- Please select the modules and quantity of each module as shown in Figure 9 and Table 4.
- Select the module and quantity required, then click "Add" button. Repeat this step for each module.
- When all modules have been selected, click "Begin" button, then "Run" button. Now, all the modules are shown in the screen.
- Click "Stop" button.
- Position each module based on layout required as shown in Figure 7. Click the module, drag and drop. Then, click "Next" button to link the elements (route for the part).

Table 4: Data for modules and its quantity

Module	Quantity
P (Part)	1
SM (Single machine)	9
SB (Single buffer)	1
SC (Single conveyor)	1
BMC (Buffer machine conveyor)	4
BML (Buffer machine labour)	3

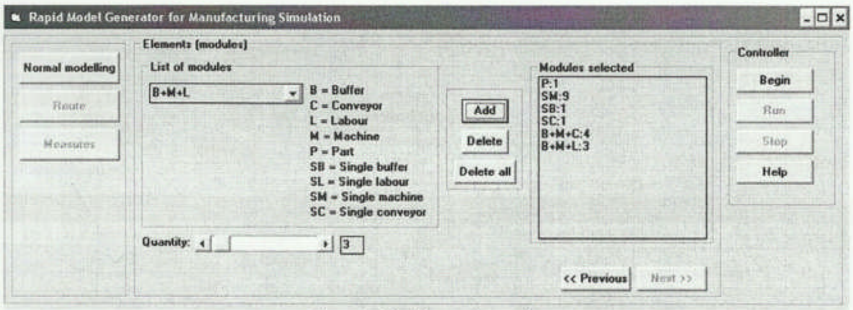

Figure 9: Modules and quantity

Step 3:

- Please add route for the part as shown in Figure 10.
- Select the first destination and click "Add" button. Repeat this step until the last destination.
- Click "Next" button and "Run" button.
- To stop the process, click "Stop" button
- Now, run the simulation model with run time at 480 unit time. Click the "Start RunAt" option on the "Execute Action Bar" at the bottom of the Witness screen. In the text box, enter the time as 480. Switch OFF the walk speed by clicking the "Walk ON/OFF" button. Then click "Run" button.
- To start again the simulation process at time 0, click "Begin" button on the prototype, then click "Run" button on the "Execute Action Bar" at the bottom of the Witness screen.

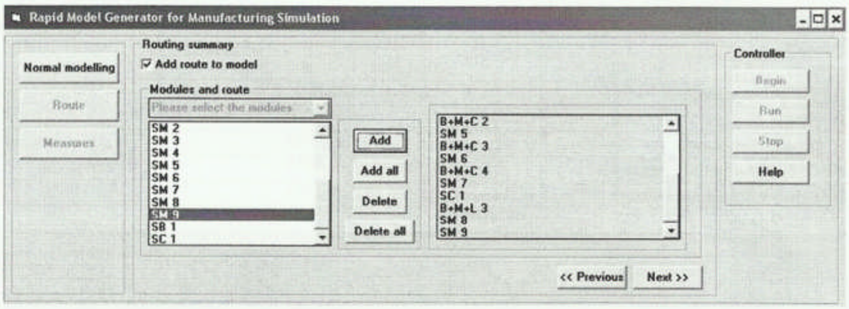

Figure 10: Routing

Evaluation: Exercise 1

	Difficult					Easy
Exercise 1	1	2	3	4	5 ✓	6

2a 2b

Exercise 2: Changing the routing (Route) 3min + 2min

Exercise 2(a): Amend the previous model with the following layout (Figure 11). Link the modules and run the model.

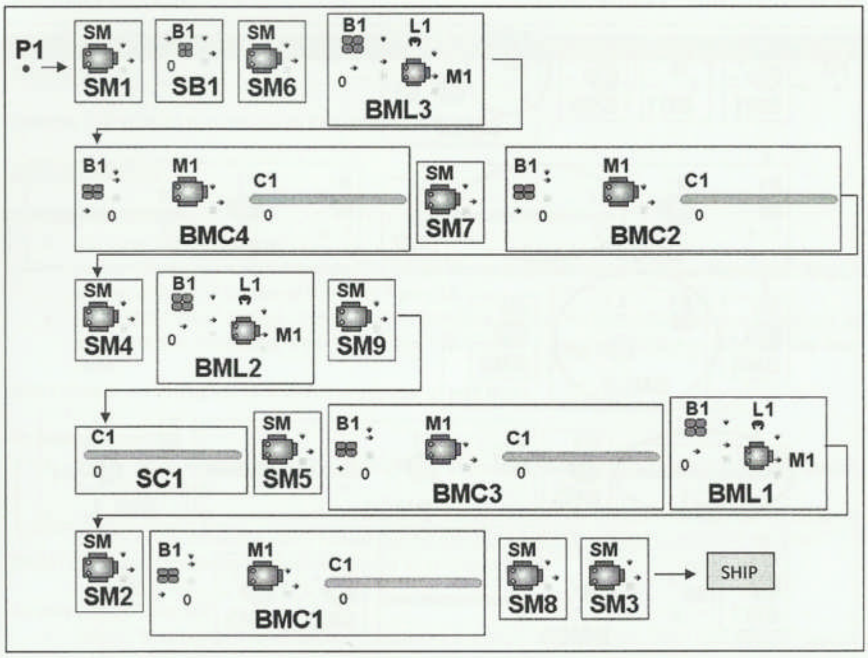

Figure 11: New layout

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 12.

Step 1:

- Click the "Route" button.
- The current route is shown in left panel. Click "Add all" button and the current route is now available in the right panel (New Route) as shown in Figure 13.
- On the "New Route" panel, select the element B1 in the "BML3" module, and click "Delete". Repeat this step for element C1 in module "BMC4". Then delete all elements in module "BML2" and module "SC1". Then click "Begin" button and "Run" button.

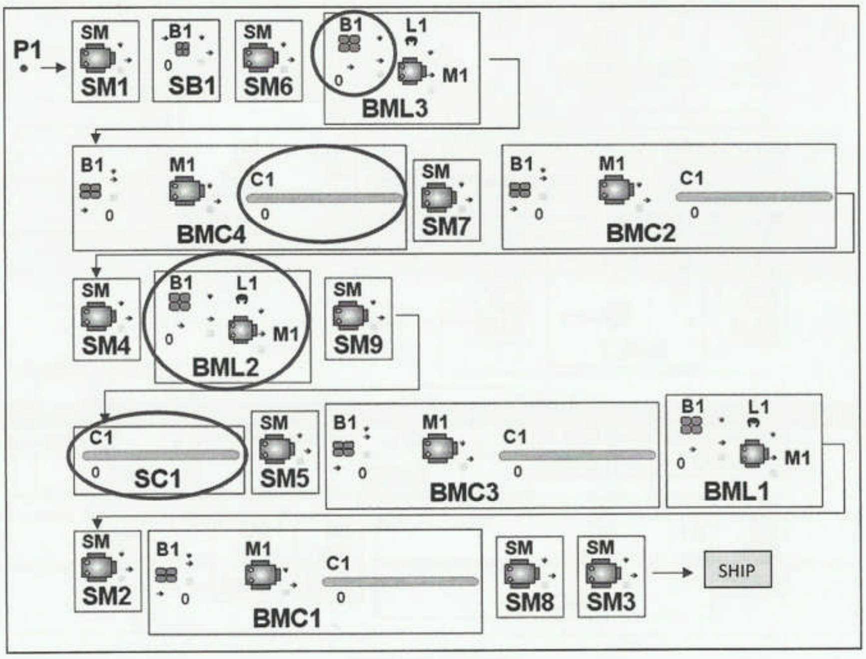

Figure 12: Changing the route

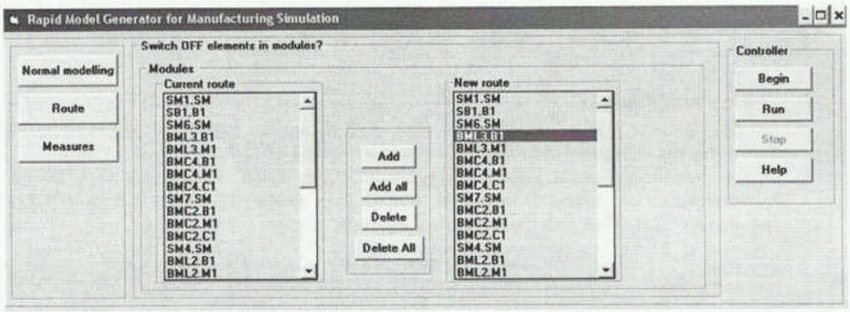

Figure 13: Switching ON/OFF elements in modules

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures (Measures)

General guidelines

To measure the lead time:

- Click the "Measures" button.
- Select "Long lead time" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button as shown in Figure 14.
- Now, click "Stop" button. A histogram is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the lead time.

(Note: Please use histogram to display the average of lead time).

To measure the WIP:

- Select "High WIP" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button.
- Now, click "Stop" button. A timeseries is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the WIP.

(Note: Please use timeseries to plot the number of WIP over time)

To detect the bottleneck:

- Select "Bottleneck" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button
- Now, click "Stop" button. Three pie charts are provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the machine utilisation.

(Note: Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

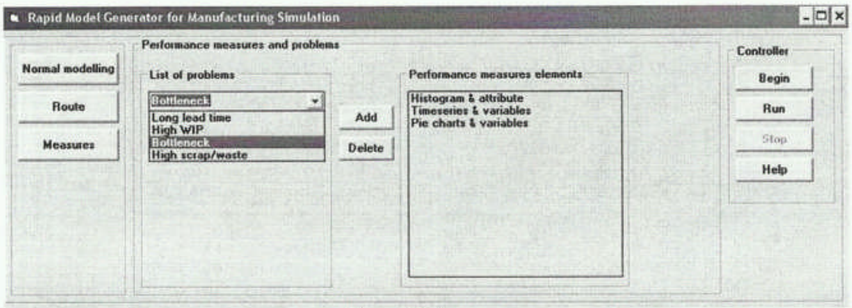

Figure 14: Measures

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 15.

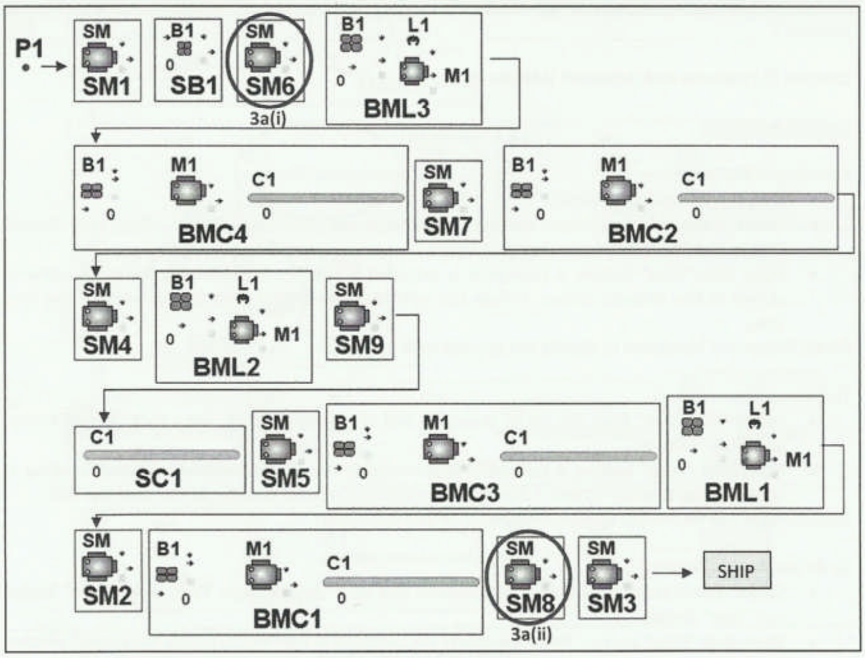

Figure 15: Exercise 3a

In order to include the breakdown in both machines, it is necessary to specify that breakdown will occur in the element (machine) details as shown in Figure 16.

15

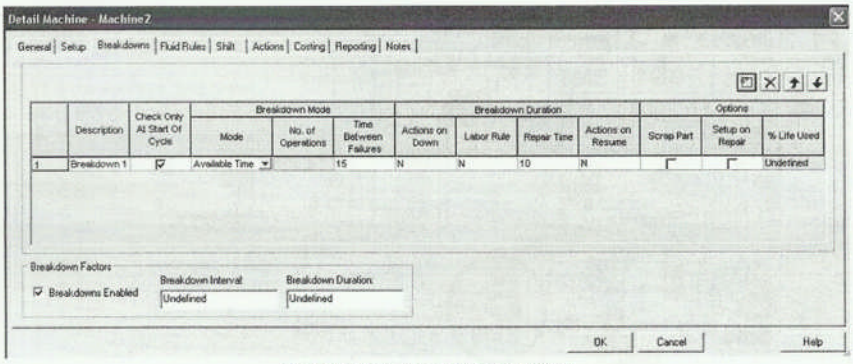

Figure 16: Data for machine breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i) 9 min	Exercise 3a(ii) 4 min
What is the average lead time?	90.40	92.31
Number of WIP (work-in-progress)?	169 [illegible] 312	175 306
What is the average of machine utilisation?	33.02%	31.87%

Evaluation: Exercise 3(a)

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

Exercise 3b: Comparing the effect of machine reliability (breakdown) for SM9 as shown in Figure 17 based on two conditions:

16

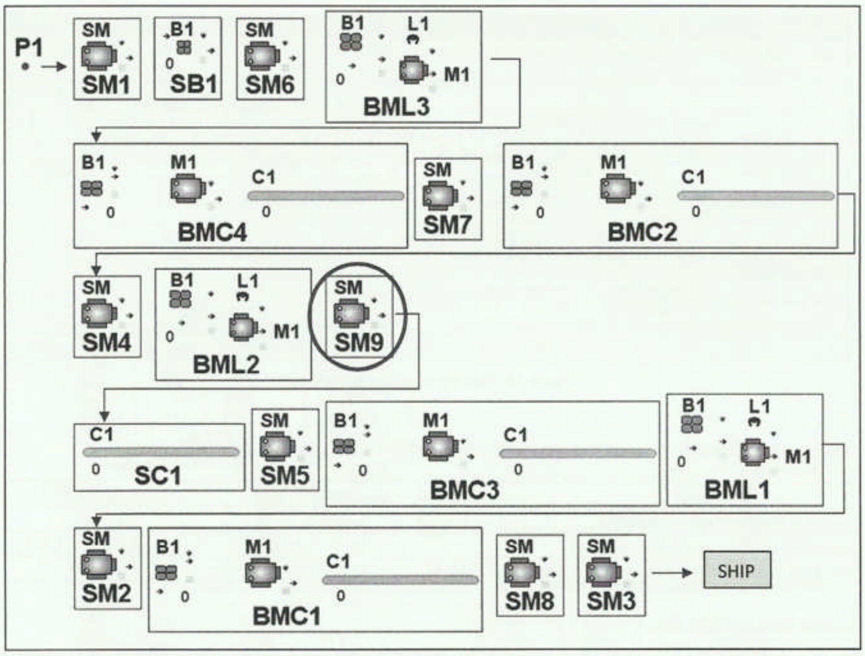

Figure 17: Exercise 3b

i. breakdown is often (short MTBF[3]) but repair time is quick (short MTTF[4])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[3] MTBF: Mean time between failures

[4] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3b(i) (4 min)	Exercise 3b(ii) (1 min)
What is the average lead time?	20	191.23
Number of WIP (work-in-progress)?	20 461	401 80
What is the average of machine utilisation?	48.21 %	8.33 %

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

The purpose of these questions is to measure to what extend this prototype can help the user to build the model. Please circle the number between 1 – 5, 1 being Strongly Disagree and 5 being Strongly Agree.

1. User experience

How long have you been involved in simulation and model building area?

Never	0 – 6 month	7 – 12 month	More than 12 month	No longer

2. Usage of Witness software (please tick)

During lectures only	
During group project	
During thesis project	
Before I came to Cranfield University	

3. Ease of use

	Strongly Disagree					Strongly Agree
The prototype is easy to use	1	2	3	4	5	6
The instructions are easy to read and understandable	1	2	3	4	5	6

4. Usefulness

	Strongly Disagree					Strongly Agree
The prototype will help me in model building	1	2	3	4	5	6
The prototype will help reduce time for model building	1	2	3	4	5	6
I can create the physical elements easily and faster	1	2	3	4	5	6
I can link the elements and run the model easily	1	2	3	4	5	6
I can switch ON/OFF any elements, link them again and run the model easily	1	2	3	4	5	6
I can easily measure the performance of the system (throughput rate, WIP, etc.)	1	2	3	4	5	6
All the elements provided for the performance measures are useful	1	2	3	4	5	6
The prototype has a lot of potential in improving model building	1	2	3	4	5	6
I will recommend this prototype to my colleagues	1	2	3	4	5	6

19

5. Visual appearance

	Strongly Disagree					Strongly Agree
The prototype displays visually pleasing design	1	2	3	4	5 ✓	6
Graphics and colour detract from actual content	1	2	3	4 ✓	5	6
The icons of the elements are easy to understand	1	2	3	4 ✓	5	6

6. Comments/suggestions

The Prototype reduces MODEL BUILDING TIME Considerably. However it causes some elements of confusion which can be addressed. It does have great potential to reduce model building time and ~~ease~~. ease.

20

Appendix F Testing and validation results (Participant 2)

Gulbert.

Rapid Model Generator for Manufacturing Simulation

Aim: To investigate a new method to rapidly build simulation model based on classification of problems using cladistics technique and template approach.

This exercise is part of the study in developing a prototype referred to as "Rapid Model Generator" in simulation modelling. Your participation in this study will help us improve the design of the prototype.

We would appreciate if you could give us your true opinion and suggestions about the prototype. Please note that we are evaluating the prototype, NOT your performance in using the software. The intention is to measure to what extent the prototype can help the user build the model.

Mode A: Building a model manually

Exercise 1: Building, linking and running a model

Please build a model as shown on Figure 1. Linking all the elements and run the model. A part is delivered to Machine1 and other elements as shown below.

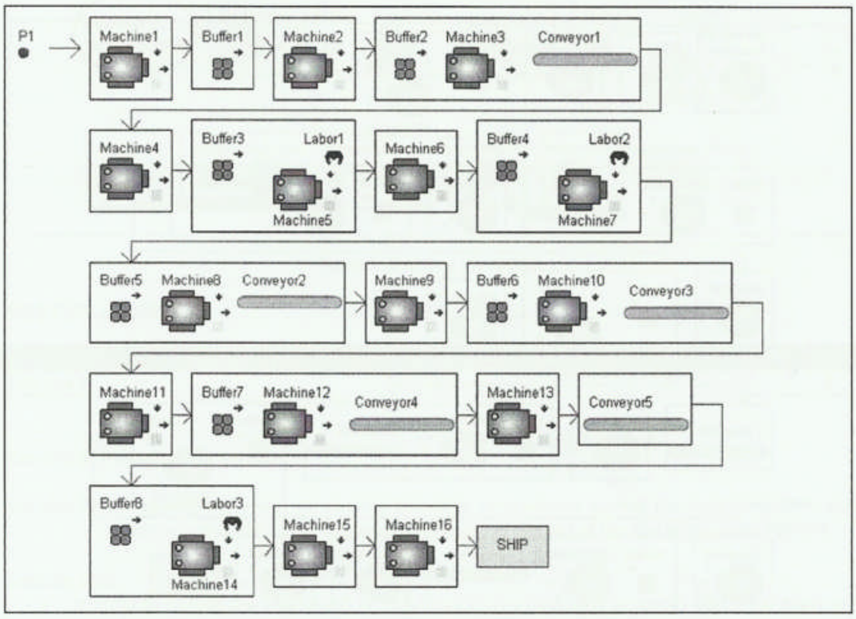

Figure 1: Layout

1

Table 1: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Evaluation: Exercise 1

	Difficult					Easy
Exercise 1	1	2	3	4	5	6

Exercise 2: Changing the routing

Exercise 2(a): Amend the previous model with the following layout (Figure 2). Link the elements and run the model.

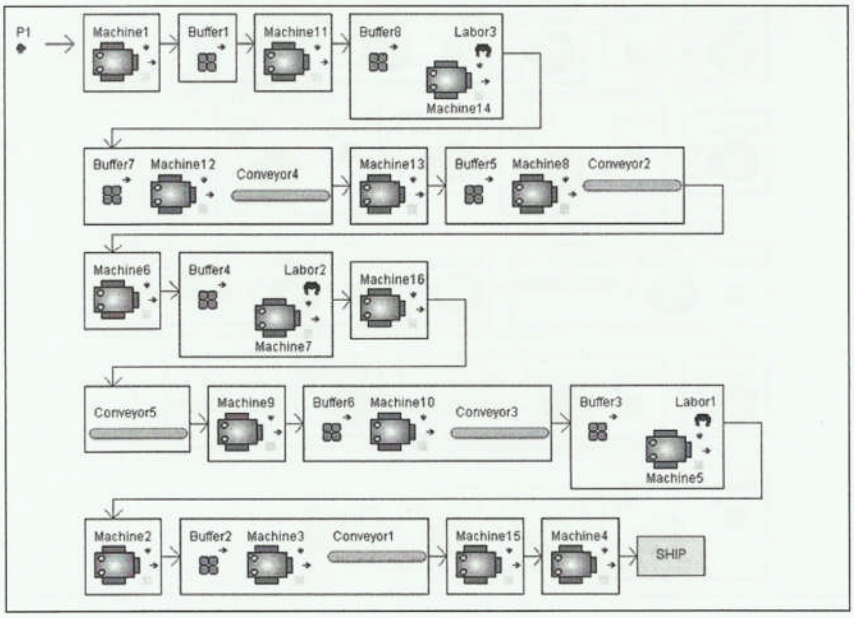

Figure 2: New layout

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 3.

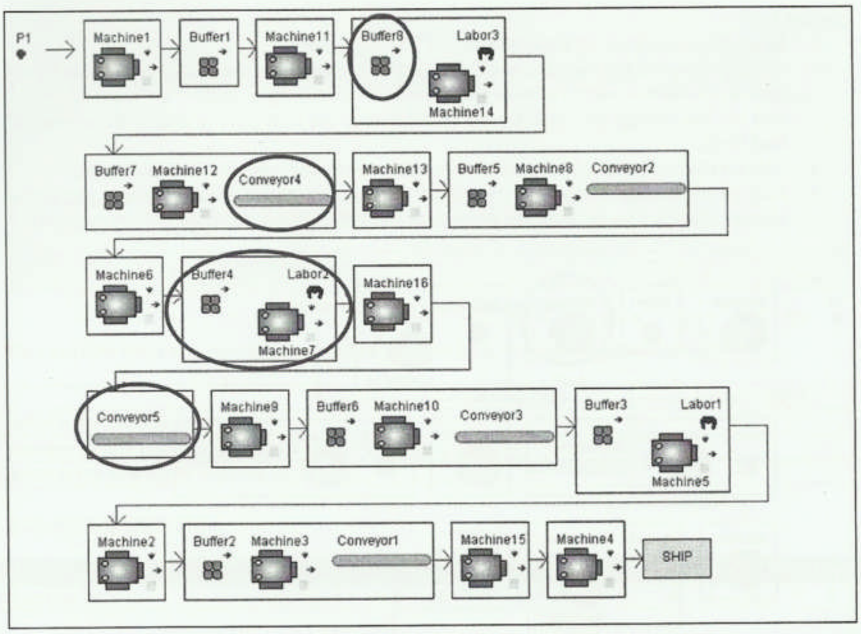

Figure 3: Changing the routing

<u>Evaluation: Exercise 2</u>

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 4.

<u>Exercise 3a(i)</u>

- In order to include the breakdown in "Machine11", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).

- Find out the average of machine utilisation ("Machine11") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3a(ii)

- Delete the breakdown details in "Machine11".
- In order to include the breakdown in "Machine15", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine15") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

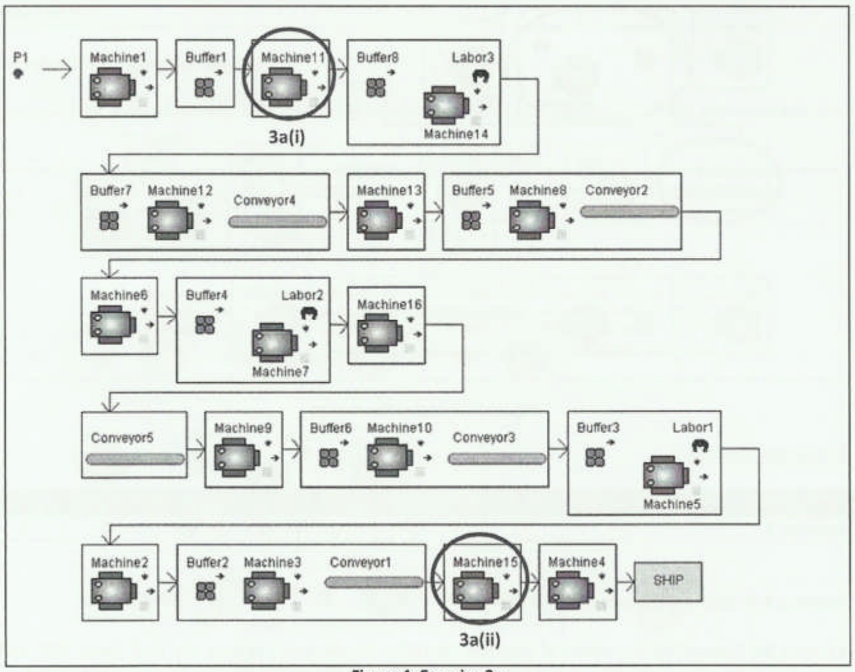

Figure 4: Exercise 3a

4

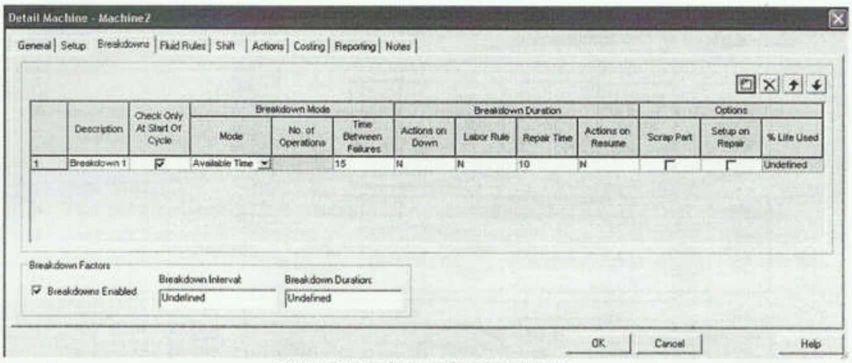

Figure 5: Data for machines breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?	Forgot cannot do it	
What is the average of machine utilisation?		

Evaluation: Exercise 3(a)

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

5

Exercise 3b: Comparing the effect of machine reliability (breakdown) for Machine16 as shown in Figure 6 based on two conditions:

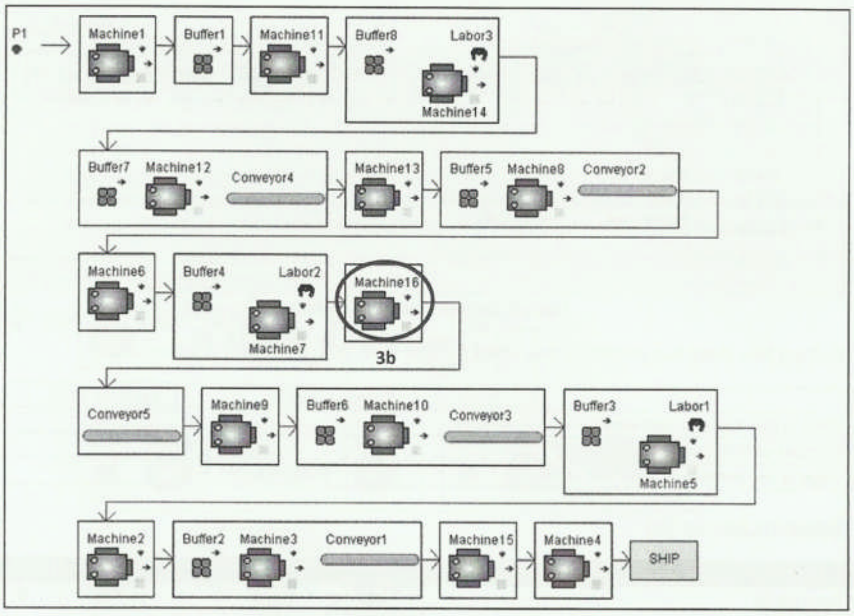

Figure 6: Exercise 3b

Table 2: Data for Exercise 3b

i. breakdown is often (short MTBF[1]) but repair time is quick (short MTTF[2])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[1] MTBF: Mean time between failures

[2] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

Exercise 3b(i)

- In order to include the breakdown in "Machine16", it is necessary to specify that breakdown will occur in the element details as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3b(ii)

- Change the details of breakdown as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

don't seem to remember the logic

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

Guibert.

Mode B: Building the model using prototype

Please follow the guidelines and instructions provided for each exercise.

Exercise 1: Building, linking and running a model (Normal Modelling)

Please build a model as shown on Figure 7. Linking all the elements and run the model. A part is delivered to SM1 and other elements as shown below.

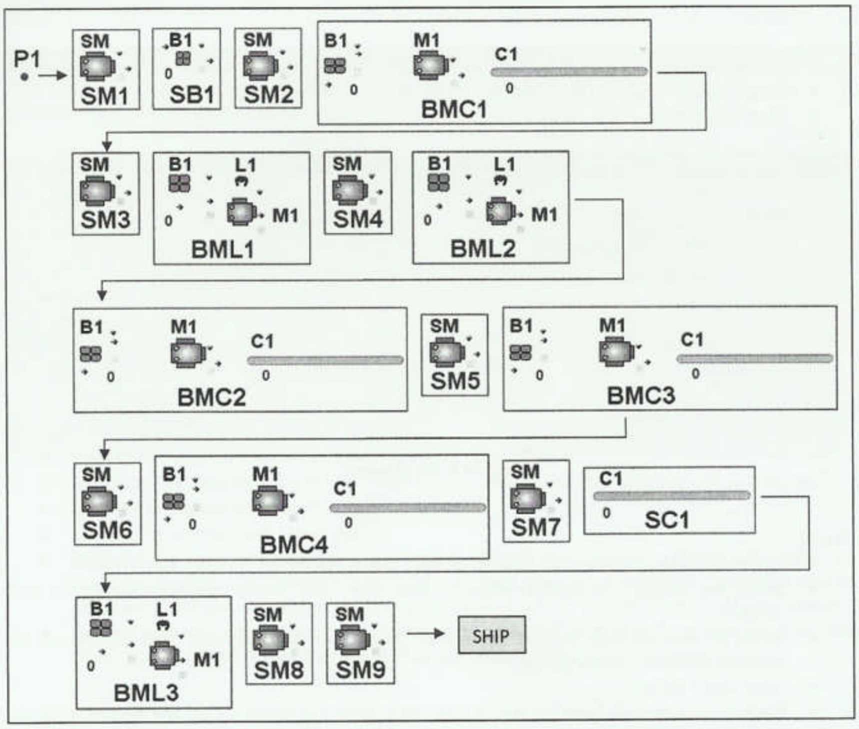

Figure 7: Layout

8

Table 3: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Step 1:

- Please select "Assembly line" from the list of layouts as shown in Figure 8.
- Click "Next" button

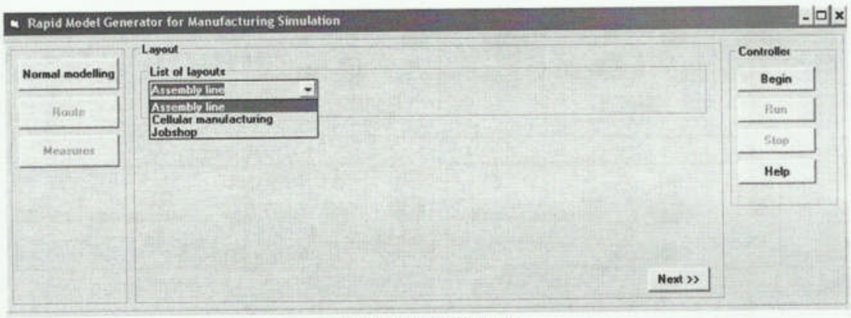

Figure 8: List of layout

Step 2:

- Please select the modules and quantity of each module as shown in Figure 9 and Table 4.
- Select the module and quantity required, then click "Add" button. Repeat this step for each module.
- When all modules have been selected, click "Begin" button, then "Run" button. Now, all the modules are shown in the screen.
- Click "Stop" button.
- Position each module based on layout required as shown in Figure 7. Click the module, drag and drop. Then, click "Next" button to link the elements (route for the part).

Table 4: Data for modules and its quantity

Module	Quantity
P (Part)	1
SM (Single machine)	9
SB (Single buffer)	1
SC (Single conveyor)	1
BMC (Buffer machine conveyor)	4
BML (Buffer machine labour)	3

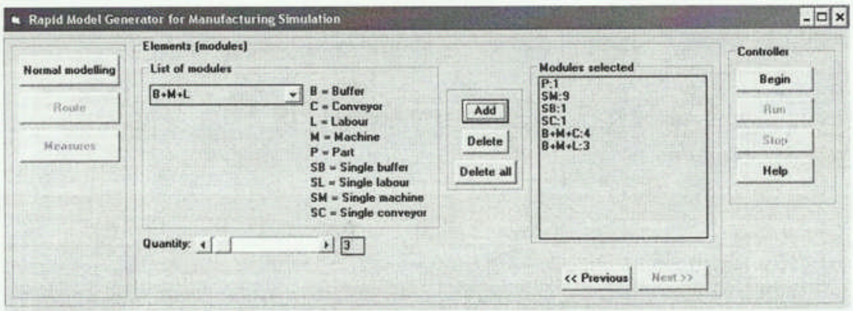

Figure 9: Modules and quantity

Step 3:

- Please add route for the part as shown in Figure 10.
- Select the first destination and click "Add" button. Repeat this step until the last destination.
- Click "Next" button and "Run" button.
- To stop the process, click "Stop" button
- Now, run the simulation model with run time at 480 unit time. Click the "Start RunAt" option on the "Execute Action Bar" at the bottom of the Witness screen. In the text box, enter the time as 480. Switch OFF the walk speed by clicking the "Walk ON/OFF" button. Then click "Run" button.
- To start again the simulation process at time 0, click "Begin" button on the prototype, then click "Run" button on the "Execute Action Bar" at the bottom of the Witness screen.

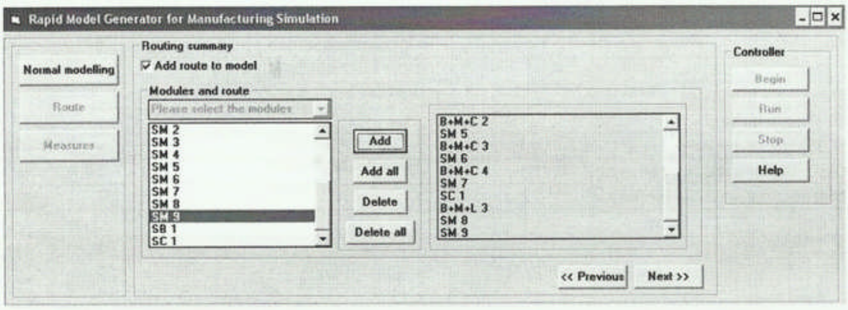

Figure 10: Routing

Evaluation: Exercise 1

	Difficult				Easy
Exercise 1	1	2	3	4	5	6

Exercise 2: Changing the routing (Route)

Exercise 2(a): Amend the previous model with the following layout (Figure 11). Link the modules and run the model.

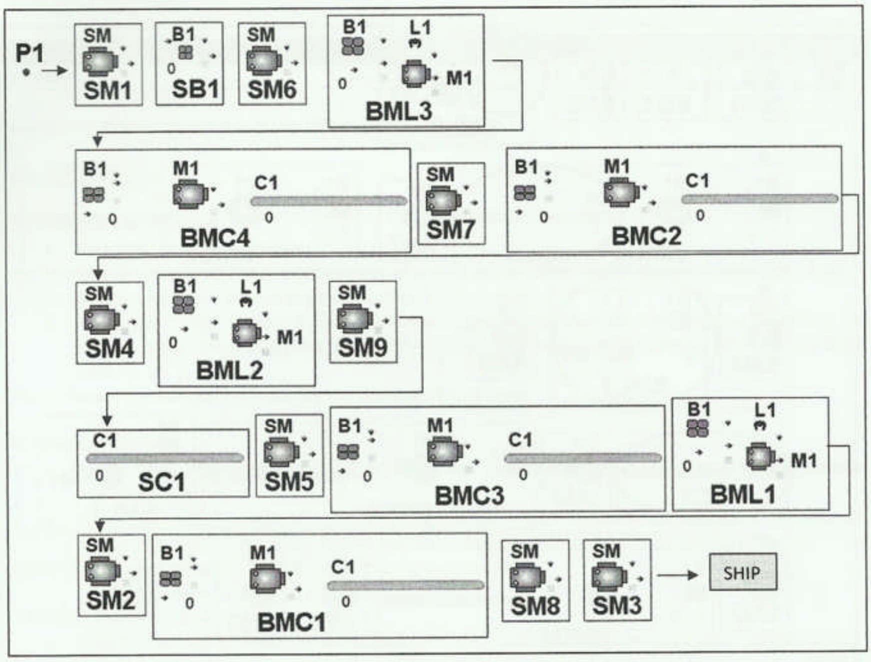

Figure 11: New layout

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 12.

Step 1:

- Click the "Route" button.
- The current route is shown in left panel. Click "Add all" button and the current route is now available in the right panel (New Route) as shown in Figure 13.
- On the "New Route" panel, select the element B1 in the "BML3" module, and click "Delete". Repeat this step for element C1 in module "BMC4". Then delete all elements in module "BML2" and module "SC1". Then click "Begin" button and "Run" button.

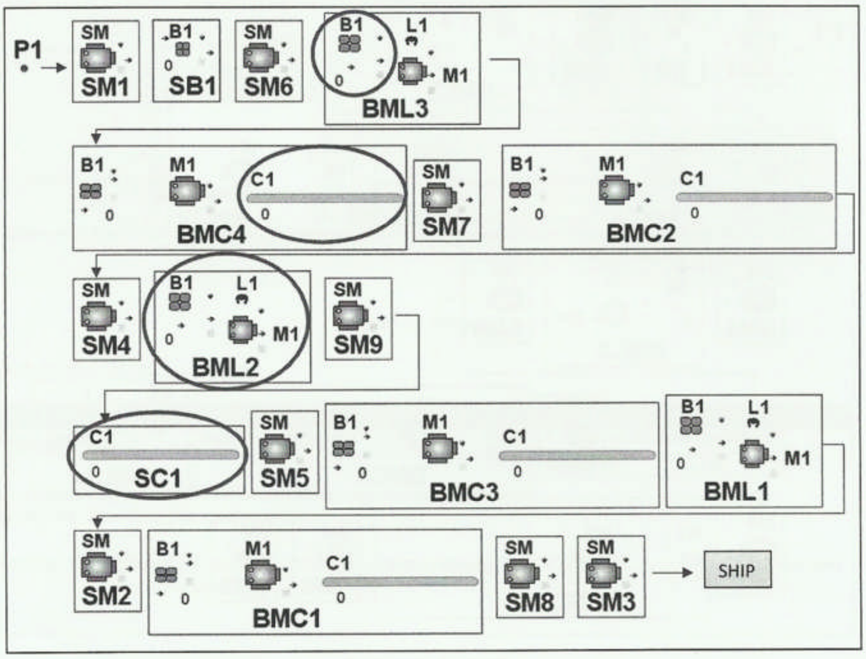

Figure 12: Changing the route

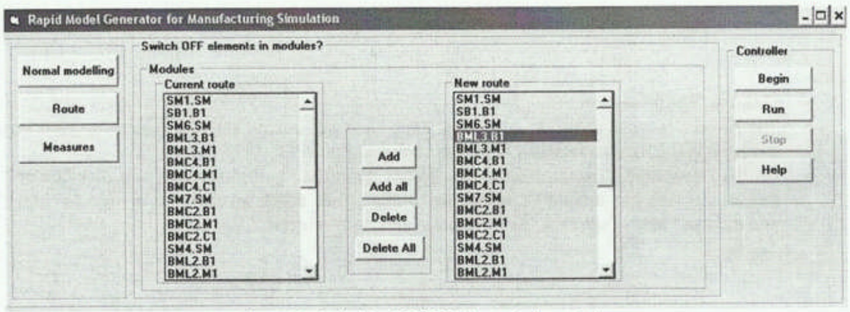

Figure 13: Switching ON/OFF elements in modules

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures (Measures)

General guidelines

To measure the lead time:

- Click the "Measures" button.
- Select "Long lead time" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button as shown in Figure 14.
- Now, click "Stop" button. A histogram is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the lead time.

(Note: Please use histogram to display the average of lead time).

To measure the WIP:

- Select "High WIP" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button.
- Now, click "Stop" button. A timeseries is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the WIP.

(Note: Please use timeseries to plot the number of WIP over time)

To detect the bottleneck:

- Select "Bottleneck" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button
- Now, click "Stop" button. Three pie charts are provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the machine utilisation.

(Note: Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

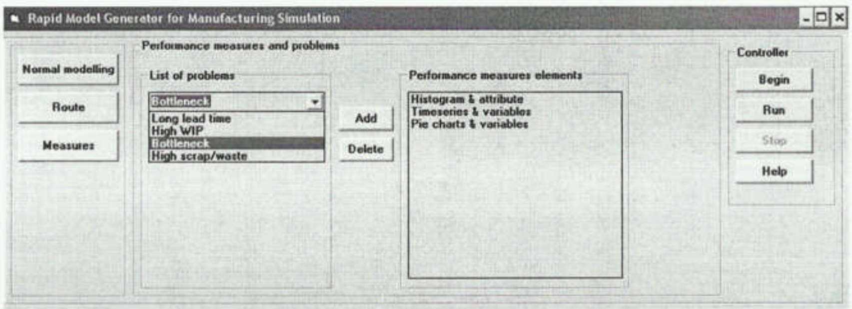

Figure 14: Measures

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 15.

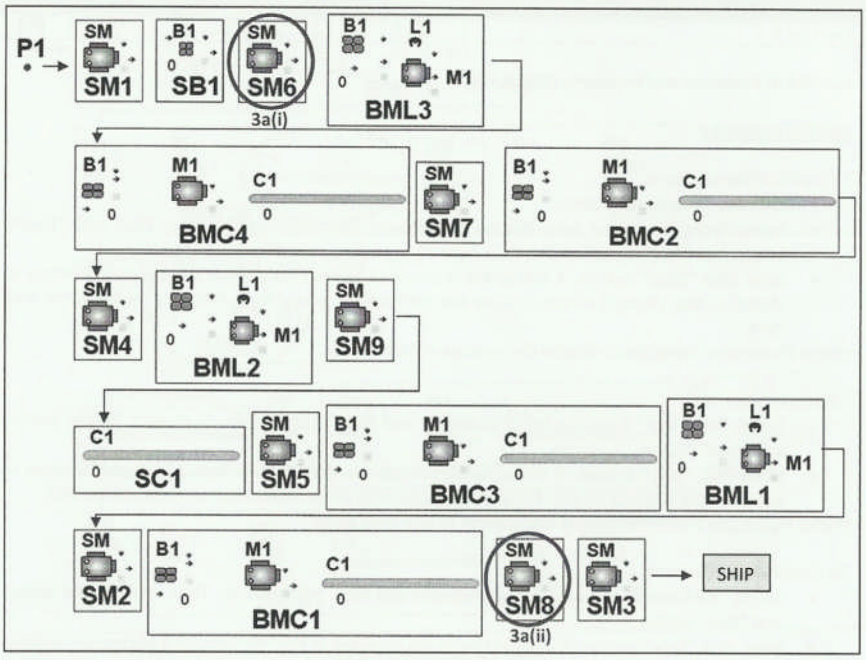

Figure 15: Exercise 3a

In order to include the breakdown in both machines, it is necessary to specify that breakdown will occur in the element (machine) details as shown in Figure 16.

15

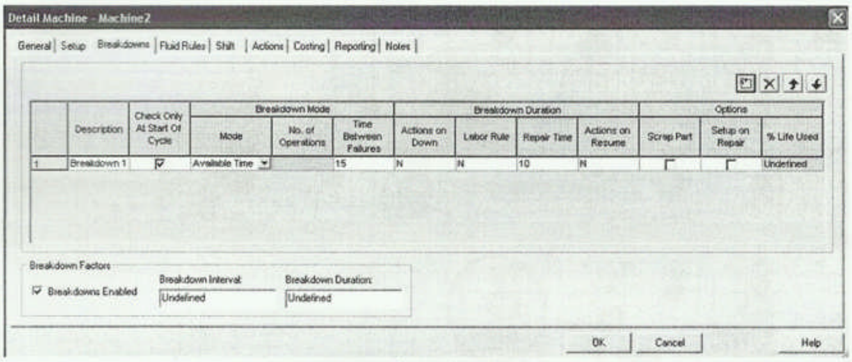

Figure 16: Data for machine breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?	~~48~~ 98	98
Number of WIP (work-in-progress)?	~~[illegible]~~ 169	175
What is the average of machine utilisation?	~~50~~ 33.02	50

<u>Evaluation: Exercise 3(a)</u>

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

Exercise 3b: Comparing the effect of machine reliability (breakdown) for SM9 as shown in Figure 17 based on two conditions:

3mins

16

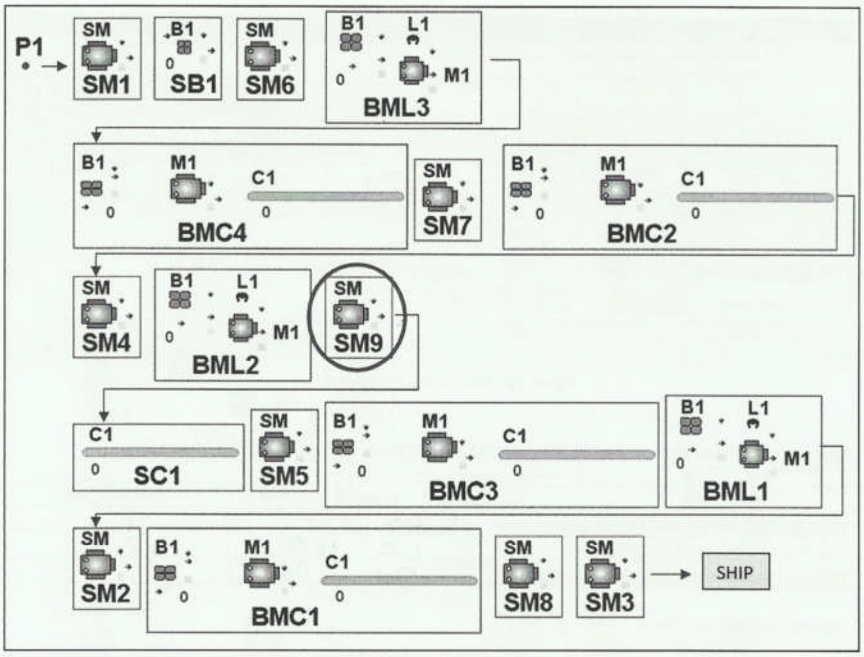

Figure 17: Exercise 3b

i. breakdown is often (short MTBF[3]) but repair time is quick (short MTTF[4])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[3] MTBF: Mean time between failures

[4] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?	450	20
Number of WIP (work-in-progress)?	20	401
What is the average of machine utilisation?	50	50

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

2 mins

18

The purpose of these questions is to measure to what extend this prototype can help the user to build the model. Please circle the number between 1 – 5, 1 being Strongly Disagree and 5 being Strongly Agree.

1. **User experience**

How long have you been involved in simulation and model building area?

Never	0 – 6 month	7 – 12 month	More than 12 month	No longer
	✓			

2. **Usage of Witness software (please tick)**

During lectures only	✓
During group project	✓X
During thesis project	✓
Before I came to Cranfield University	X

3. **Ease of use**

	Strongly Disagree					Strongly Agree
The prototype is easy to use	1	2	3	4	5	6
The instructions are easy to read and understandable	1	2	3	4	5	6

4. **Usefulness**

	Strongly Disagree					Strongly Agree
The prototype will help me in model building	1	2	3	4	5	6
The prototype will help reduce time for model building	1	2	3	4	5	6
I can create the physical elements easily and faster	1	2	3	4	5	6
I can link the elements and run the model easily	1	2	3	4	5	6
I can switch ON/OFF any elements, link them again and run the model easily	1	2	3	4	5	6
I can easily measure the performance of the system (throughput rate, WIP, etc.)	1	2	3	4	5	6
All the elements provided for the performance measures are useful	1	2	3	4	5	6
The prototype has a lot of potential in improving model building	1	2	3	4	5	6
I will recommend this prototype to my colleagues	1	2	3	4	5	6

19

5. Visual appearance

	Strongly Disagree					Strongly Agree
The prototype displays visually pleasing design	1	2	3	4	5	6
Graphics and colour detract from actual content	1	2	3	4	5	6
The icons of the elements are easy to understand	1	2	3	4	5	6

6. Comments/suggestions

Eliminate the dragging by using co-ordinates for locating elements.

Appendix G Testing and validation results (Participant 3)

Kiran

Rapid Model Generator for Manufacturing Simulation

Aim: To investigate a new method to rapidly build simulation model based on classification of problems using cladistics technique and template approach.

This exercise is part of the study in developing a prototype referred to as "Rapid Model Generator" in simulation modelling. Your participation in this study will help us improve the design of the prototype.

We would appreciate if you could give us your true opinion and suggestions about the prototype. Please note that we are evaluating the prototype, NOT your performance in using the software. The intention is to measure to what extent the prototype can help the user build the model.

Mode A: Building a model manually

Exercise 1: Building, linking and running a model

Please build a model as shown on Figure 1. Linking all the elements and run the model. A part is delivered to Machine1 and other elements as shown below.

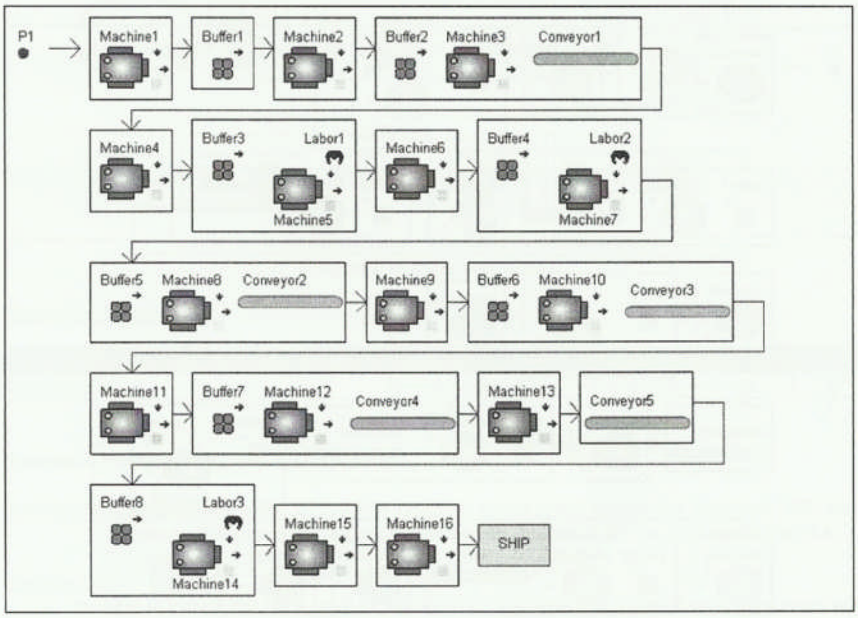

Figure 1: Layout

1

Table 1: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Evaluation: Exercise 1

	Difficult					Easy
Exercise 1	1	2	3	4	5	6

Exercise 2: Changing the routing

Exercise 2(a): Amend the previous model with the following layout (Figure 2). Link the elements and run the model.

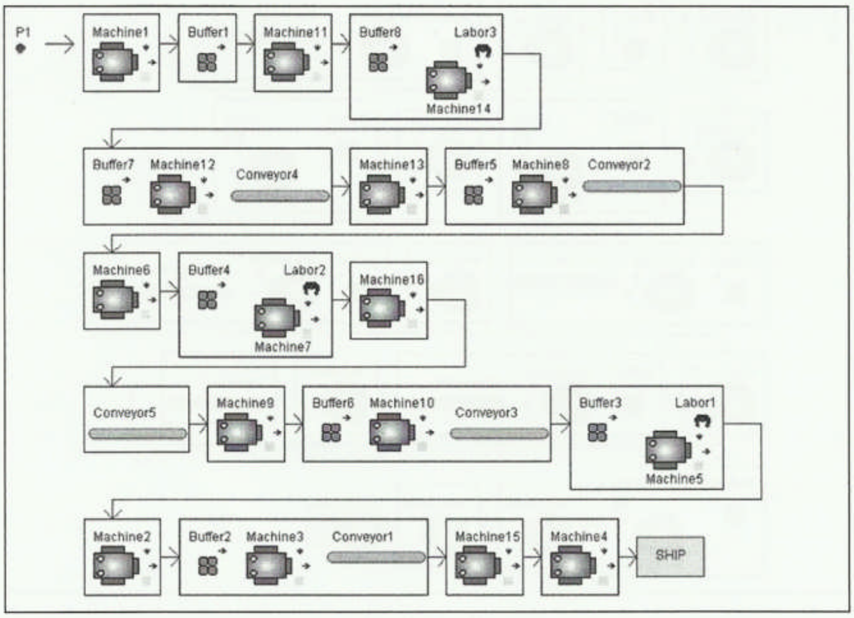

Figure 2: New layout

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 3.

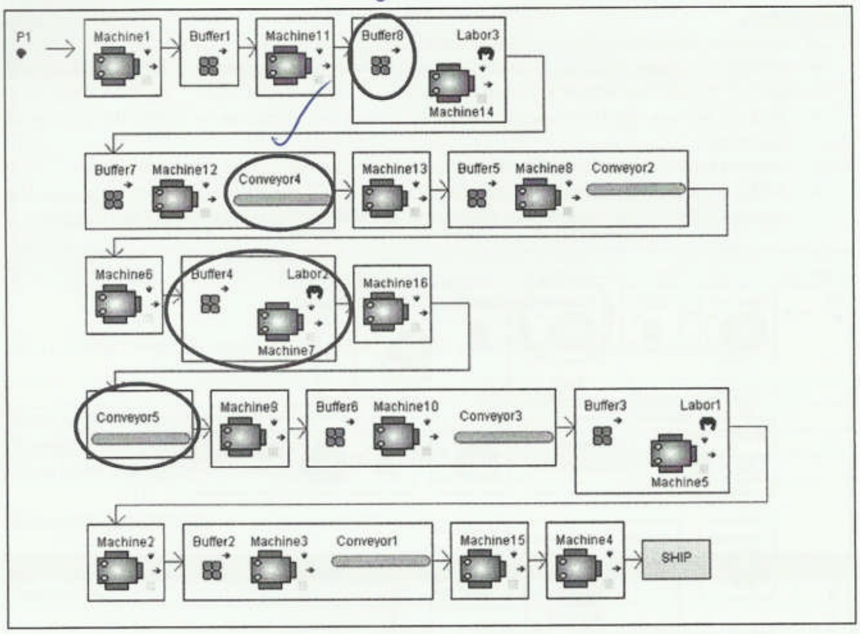

Figure 3: Changing the routing

Evaluation: Exercise 2

	Difficult				Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 4.

Exercise 3a(i)

- In order to include the breakdown in "Machine11", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).

- Find out the average of machine utilisation ("Machine11") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3a(ii)

- Delete the breakdown details in "Machine11".
- In order to include the breakdown in "Machine15", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine15") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

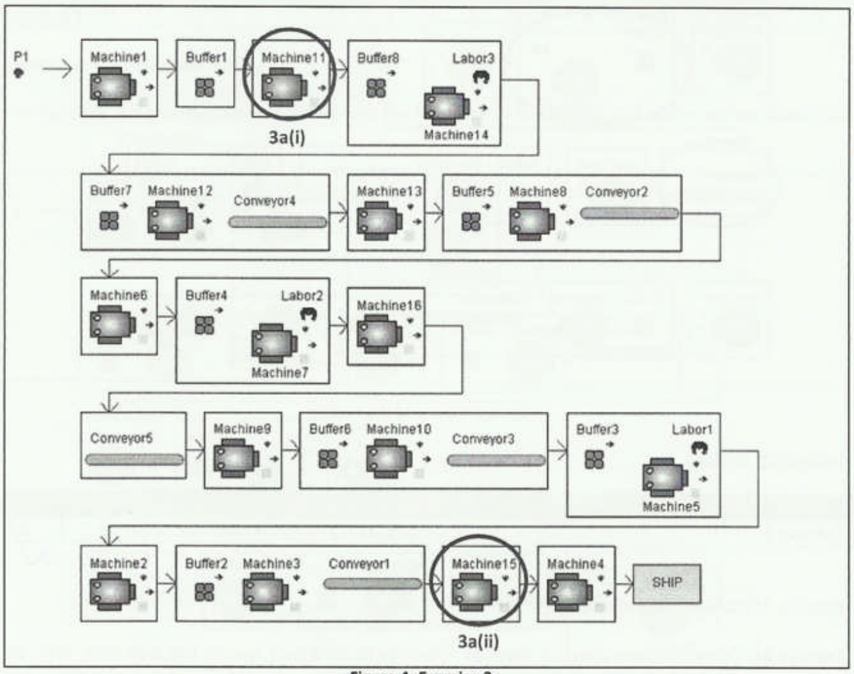

Figure 4: Exercise 3a

4

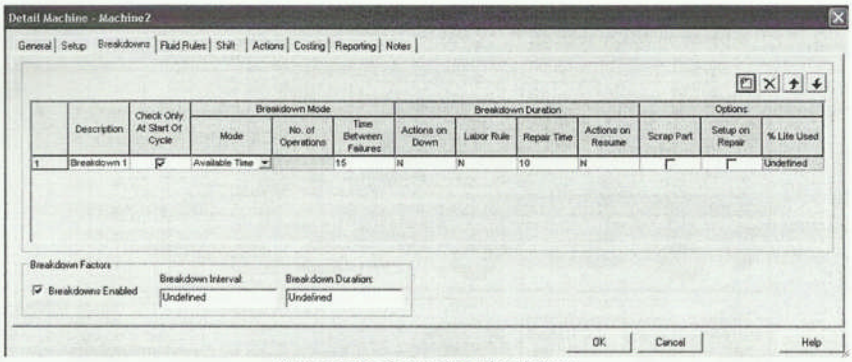

Figure 5: Data for machines breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

<u>Evaluation: Exercise 3(a)</u>

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

I cannot measure WIP, Avg lead time etc.

Exercise 3b: Comparing the effect of machine reliability (breakdown) for Machine16 as shown in Figure 6 based on two conditions:

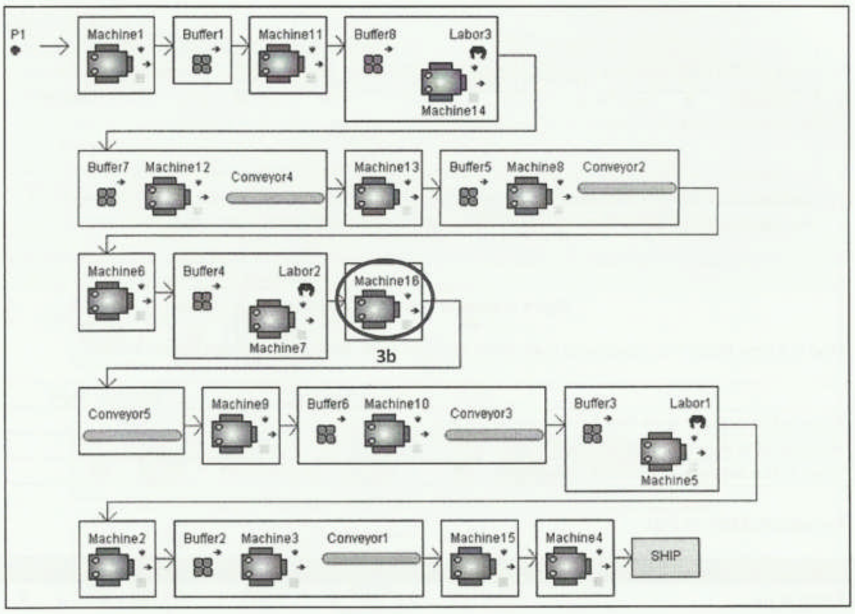

Figure 6: Exercise 3b

Table 2: Data for Exercise 3b

i. breakdown is often (short MTBF[1]) but repair time is quick (short MTTF[2])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[1] MTBF: Mean time between failures

[2] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

Exercise 3b(i)

- In order to include the breakdown in "Machine16", it is necessary to specify that breakdown will occur in the element details as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3b(ii)

- Change the details of breakdown as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2 ✓	3	4	5	6

I Don't know how to Do WIP, Lead Time.

Kiran

Mode B: Building the model using prototype

Please follow the guidelines and instructions provided for each exercise.

Exercise 1: Building, linking and running a model (Normal Modelling) 7 min

Please build a model as shown on Figure 7. Linking all the elements and run the model. A part is delivered to SM1 and other elements as shown below.

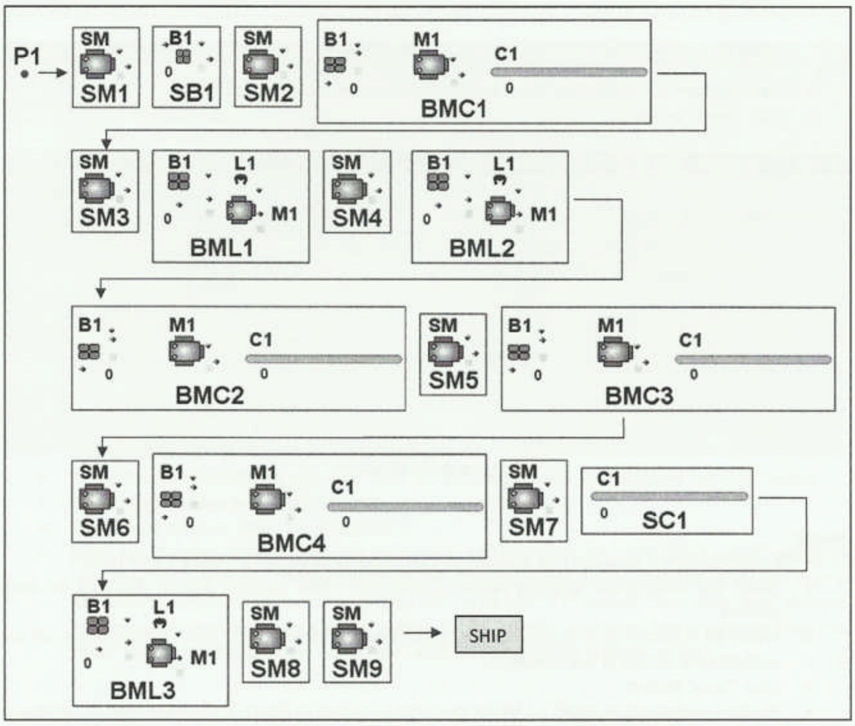

Figure 7: Layout

8

Table 3: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Step 1:

- Please select "Assembly line" from the list of layouts as shown in Figure 8.
- Click "Next" button

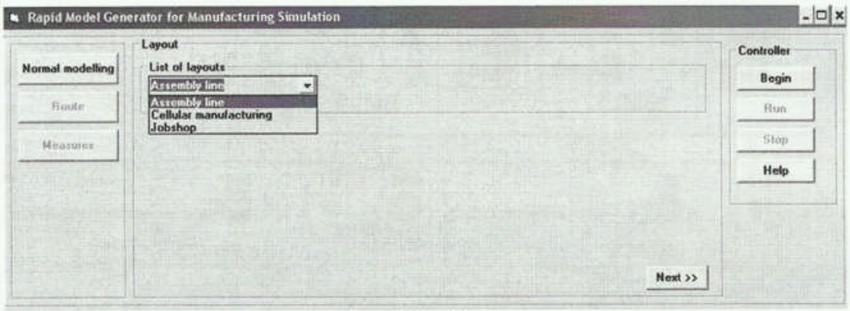

Figure 8: List of layout

Step 2:

- Please select the modules and quantity of each module as shown in Figure 9 and Table 4.
- Select the module and quantity required, then click "Add" button. Repeat this step for each module.
- When all modules have been selected, click "Begin" button, then "Run" button. Now, all the modules are shown in the screen.
- Click "Stop" button.
- Position each module based on layout required as shown in Figure 7. Click the module, drag and drop. Then, click "Next" button to link the elements (route for the part).

Table 4: Data for modules and its quantity

Module	Quantity
P (Part)	1
SM (Single machine)	9
SB (Single buffer)	1
SC (Single conveyor)	1
BMC (Buffer machine conveyor)	4
BML (Buffer machine labour)	3

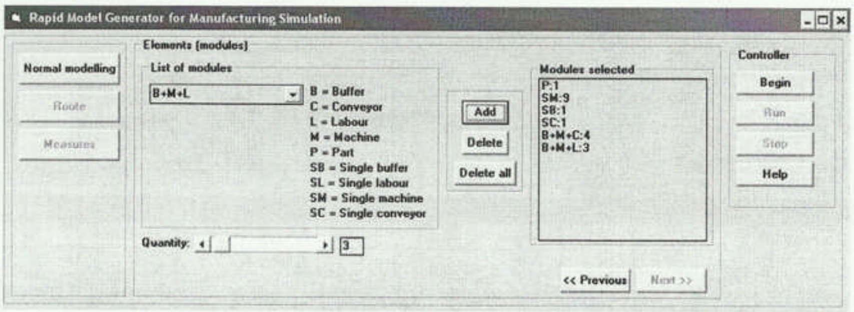

Figure 9: Modules and quantity

Step 3:

- Please add route for the part as shown in Figure 10.
- Select the first destination and click "Add" button. Repeat this step until the last destination.
- Click "Next" button and "Run" button.
- To stop the process, click "Stop" button
- Now, run the simulation model with run time at 480 unit time. Click the "Start RunAt" option on the "Execute Action Bar" at the bottom of the Witness screen. In the text box, enter the time as 480. Switch OFF the walk speed by clicking the "Walk ON/OFF" button. Then click "Run" button.
- To start again the simulation process at time 0, click "Begin" button on the prototype, then click "Run" button on the "Execute Action Bar" at the bottom of the Witness screen.

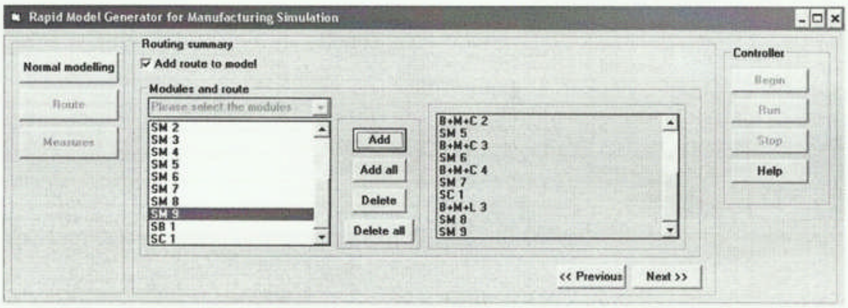

Figure 10: Routing

Evaluation: Exercise 1

	Difficult					Easy
Exercise 1	1	2	3	4	5	6 ✓

2a 2b

Exercise 2: Changing the routing (Route) 4 min + 1 min = 5 min

Exercise 2(a): Amend the previous model with the following layout (Figure 11). Link the modules and run the model.

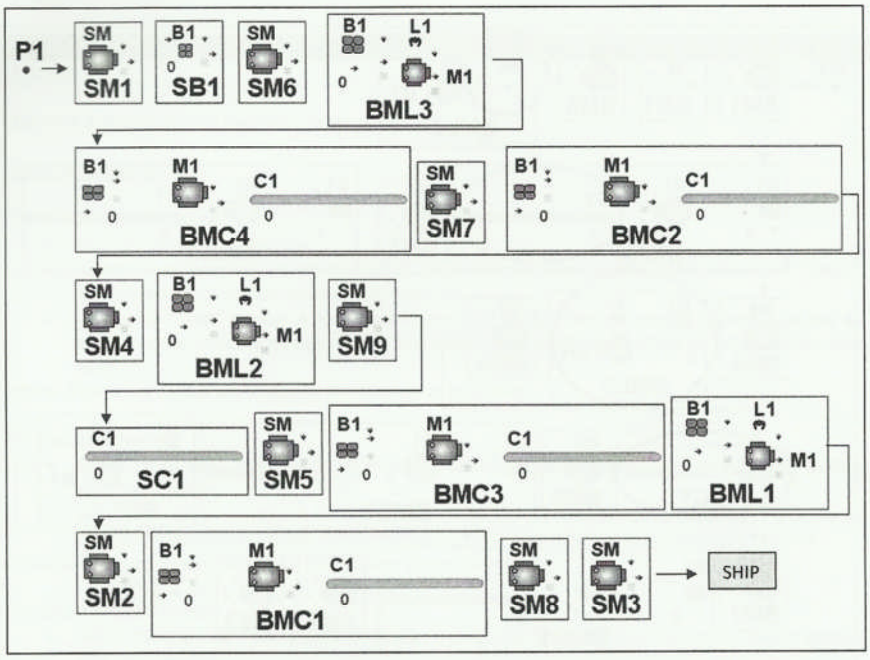

Figure 11: New layout

took 2 minutes

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 12.

Step 1:

- Click the "Route" button.
- The current route is shown in left panel. Click "Add all" button and the current route is now available in the right panel (New Route) as shown in Figure 13.
- On the "New Route" panel, select the element B1 in the "BML3" module, and click "Delete". Repeat this step for element C1 in module "BMC4". Then delete all elements in module "BML2" and module "SC1". Then click "Begin" button and "Run" button.

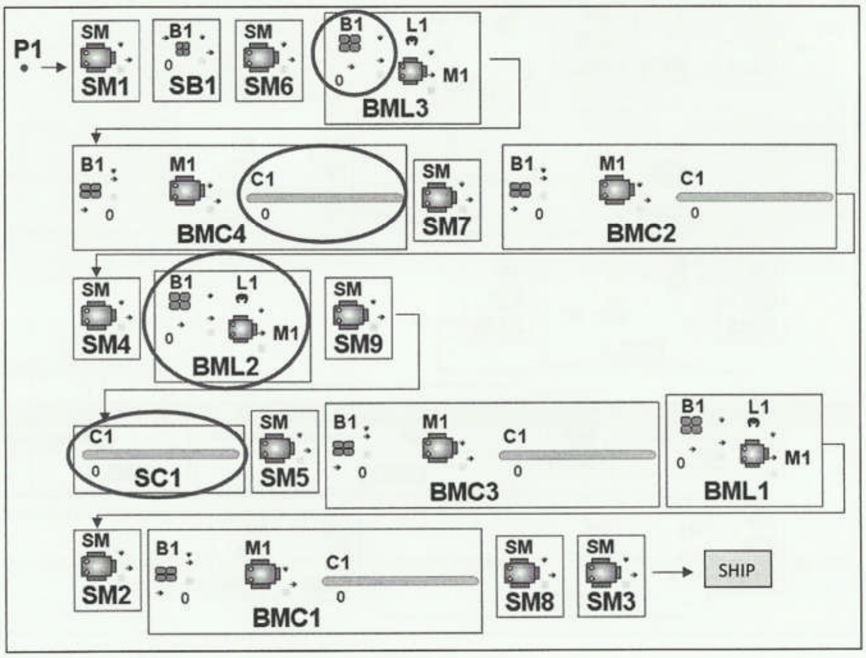

Figure 12: Changing the route

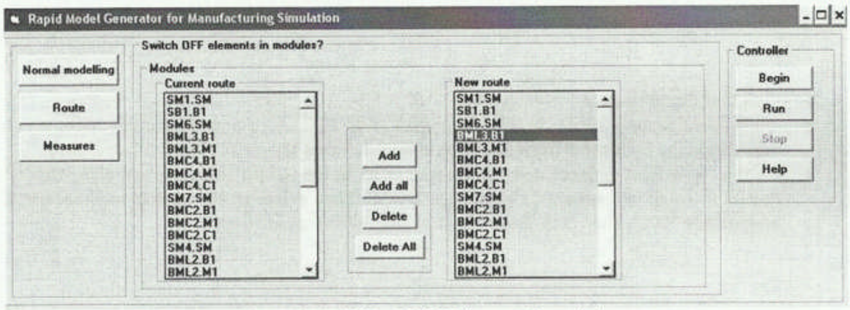

Figure 13: Switching ON/OFF elements in modules

took 2 mins to complete

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures (Measures)

General guidelines

To measure the lead time:

- Click the "Measures" button.
- Select "Long lead time" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button as shown in Figure 14.
- Now, click "Stop" button. A histogram is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the lead time.

(Note: Please use histogram to display the average of lead time).

To measure the WIP:

- Select "High WIP" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button.
- Now, click "Stop" button. A timeseries is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the WIP.

(Note: Please use timeseries to plot the number of WIP over time)

To detect the bottleneck:

- Select "Bottleneck" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button
- Now, click "Stop" button. Three pie charts are provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the machine utilisation.

(Note: Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

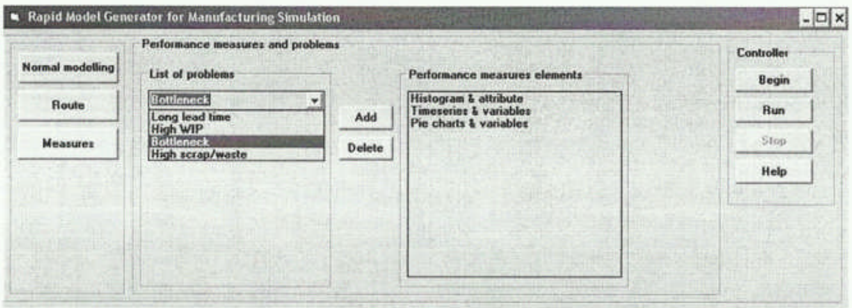

Figure 14: Measures

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 15.

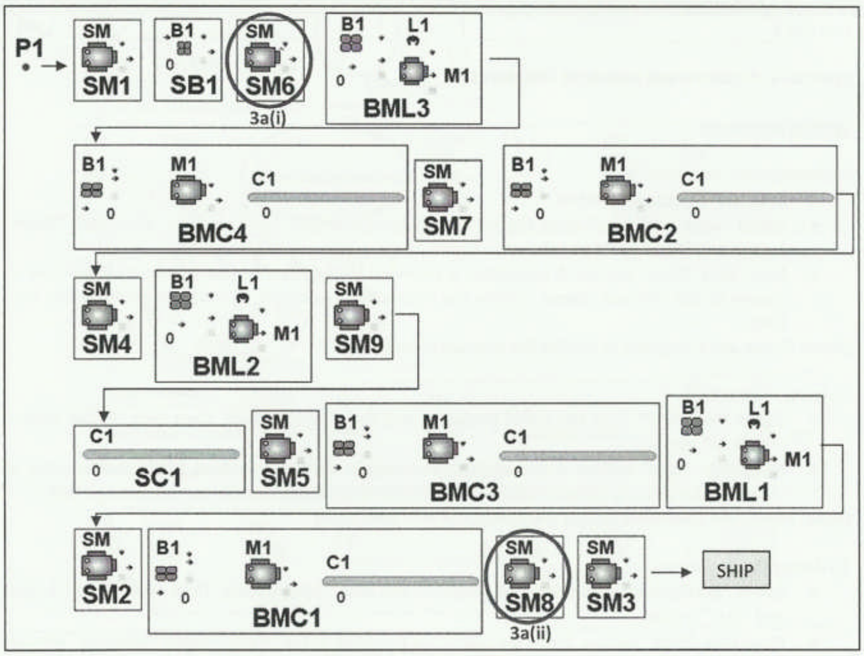

Figure 15: Exercise 3a

In order to include the breakdown in both machines, it is necessary to specify that breakdown will occur in the element (machine) details as shown in Figure 16.

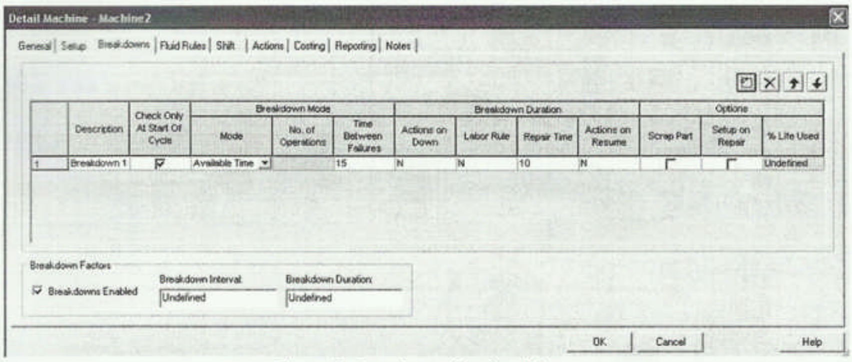

Figure 16: Data for machine breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i) 9 min	Exercise 3a(ii) 4 min
What is the average lead time?	90·40	96·31
Number of WIP (work-in-progress)?	169 + ? 312	175 / 1hr - 30h
What is the average of machine utilisation?	33·02 ·	31·87 ·

Evaluation: Exercise 3(a)

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

Exercise 3b: Comparing the effect of machine reliability (breakdown) for SM9 as shown in Figure 17 based on two conditions:

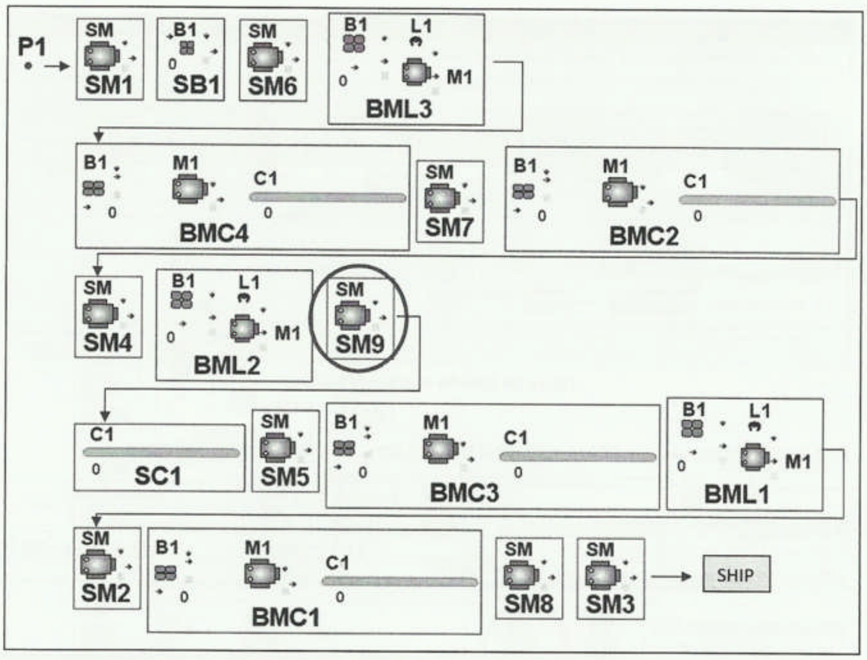

Figure 17: Exercise 3b

i. breakdown is often (short MTBF[3]) but repair time is quick (short MTTF[4])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[3] MTBF: Mean time between failures

[4] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	3 min Exercise 3b(i)	2 min Exercise 3b(ii)
What is the average lead time?	20·28	191·23 ·
Number of WIP (work-in-progress)?	20 | 8hr → 461	401 | 8hr – 80
What is the average of machine utilisation?	48·21	8·33

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	✓6

3

The purpose of these questions is to measure to what extend this prototype can help the user to build the model. Please circle the number between 1 – 5, 1 being Strongly Disagree and 5 being Strongly Agree.

1. **User experience**

How long have you been involved in simulation and model building area?

Never	0 – 6 month	7 – 12 month	More than 12 month	No longer
	✓			

2. **Usage of Witness software (please tick)**

During lectures only	✓
During group project	
During thesis project	
Before I came to Cranfield University	

3. **Ease of use**

	Strongly Disagree					Strongly Agree
The prototype is easy to use	1	2	3	4	5 ✓	6
The instructions are easy to read and understandable	1	2	3	4 ✓	5	6

4. **Usefulness**

	Strongly Disagree					Strongly Agree
The prototype will help me in model building	1	2	3	4	✓ 5	6
The prototype will help reduce time for model building	1	2	3	4	✓ 5	6
I can create the physical elements easily and faster (using witness)	1	2 ✓	3	4	5	6
I can link the elements and run the model easily (using witness)	1	2 ✓	3	4	5	6
I can switch ON/OFF any elements, link them again and run the model easily (using witness)	1	2 ✓	3	4	5	6
I can easily measure the performance of the system (throughput rate, WIP, etc.)	1	2	3 ✓	4	5	6
All the elements provided for the performance measures are useful	1	2	3	4	5 ✓	6
The prototype has a lot of potential in improving model building	1	2	3	4	5 ✓	6
I will recommend this prototype to my colleagues	1	2	3	4	5 ✓	6

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5. **Visual appearance**

	Strongly Disagree					Strongly Agree
The prototype displays visually pleasing design	1	2	3	4 ✓	5	6
Graphics and colour detract from actual content	1	2 ✓	3	4	5	6
The icons of the elements are easy to understand	1	2	3	4 ✓	5	6

6. **Comments/suggestions**

The model would be very useful for persons with a little bit of knowledge about WITNESS.
For a beginner without no knowledge about simulation it will be the same.
Some of the features of the model is very good. It will be useful for quick simulation run of any systems in a factory.

Appendix H Testing and validation results (Participant 4)

Steenesby

Rapid Model Generator for Manufacturing Simulation

Aim: To investigate a new method to rapidly build simulation model based on classification of problems using cladistics technique and template approach.

This exercise is part of the study in developing a prototype referred to as "Rapid Model Generator" in simulation modelling. Your participation in this study will help us improve the design of the prototype.

We would appreciate if you could give us your true opinion and suggestions about the prototype. Please note that we are evaluating the prototype, NOT your performance in using the software. The intention is to measure to what extent the prototype can help the user build the model.

Mode A: Building a model manually

Exercise 1: Building, linking and running a model

Please build a model as shown on Figure 1. Linking all the elements and run the model. A part is delivered to Machine1 and other elements as shown below.

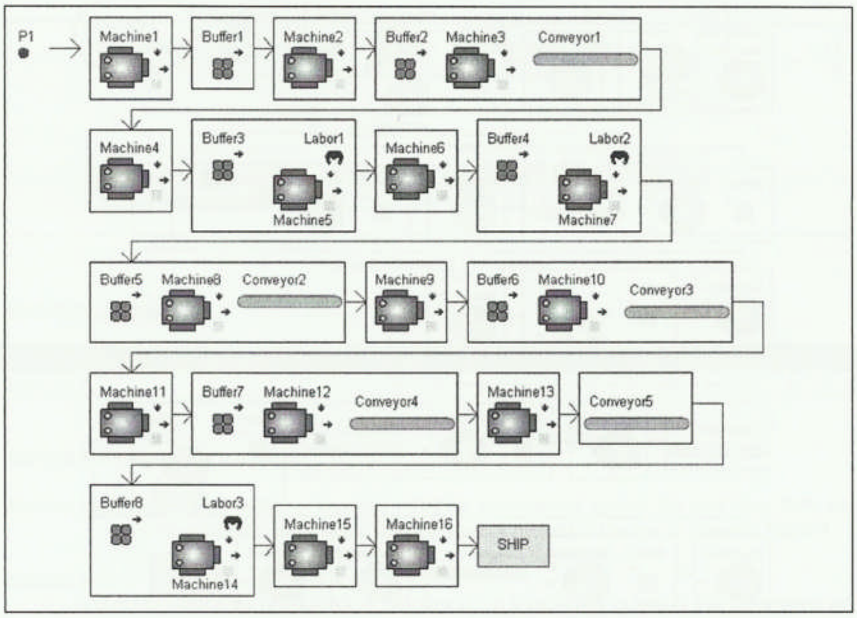

Figure 1: Layout

It is completed

1

Table 1: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Evaluation: Exercise 1

	Difficult					Easy
Exercise 1	1	2	3	4	5	6

Exercise 2: Changing the routing

Exercise 2(a): Amend the previous model with the following layout (Figure 2). Link the elements and run the model.

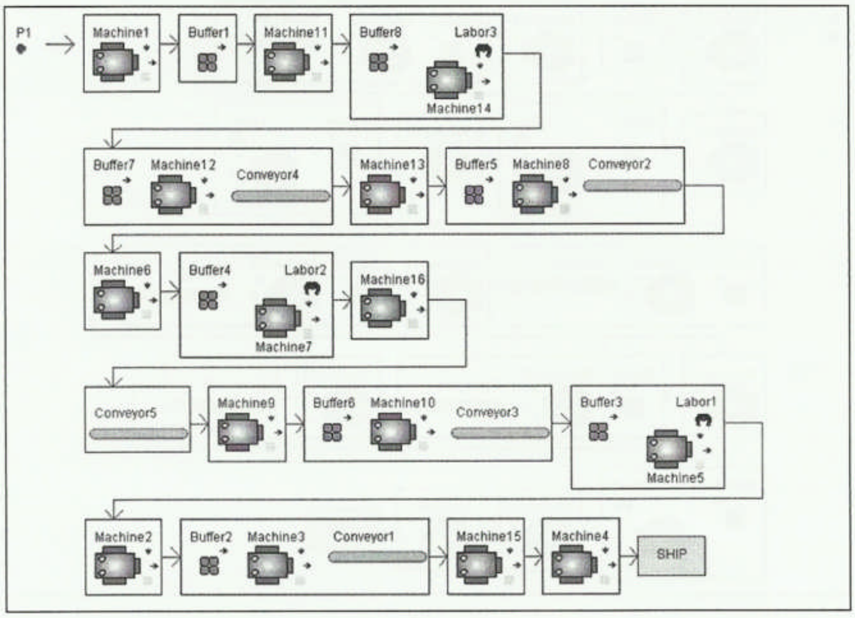

Figure 2: New layout

It is completed

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 3.

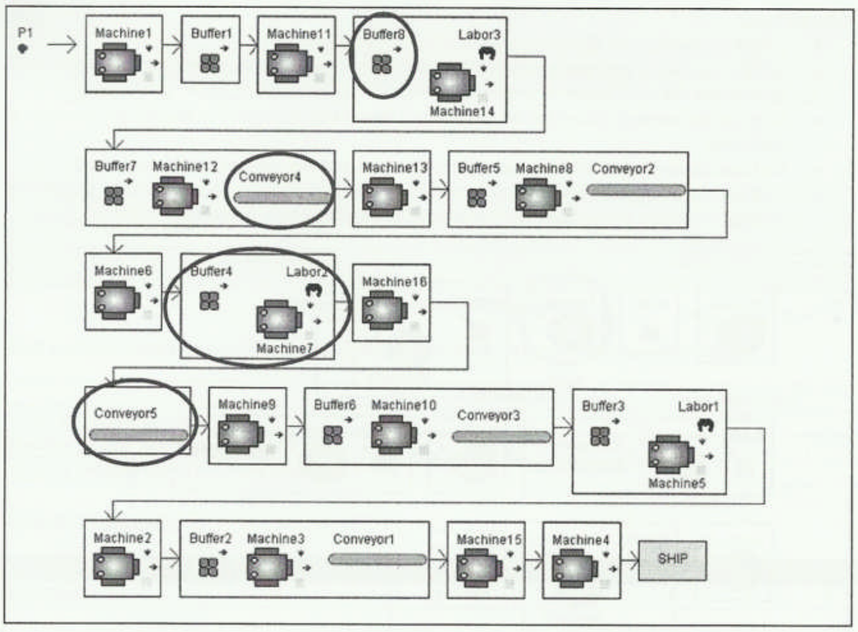

Figure 3: Changing the routing

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 4.

Exercise 3a(i)

- In order to include the breakdown in "Machine11", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).

- Find out the average of machine utilisation ("Machine11") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3a(ii)

- Delete the breakdown details in "Machine11".
- In order to include the breakdown in "Machine15", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine15") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

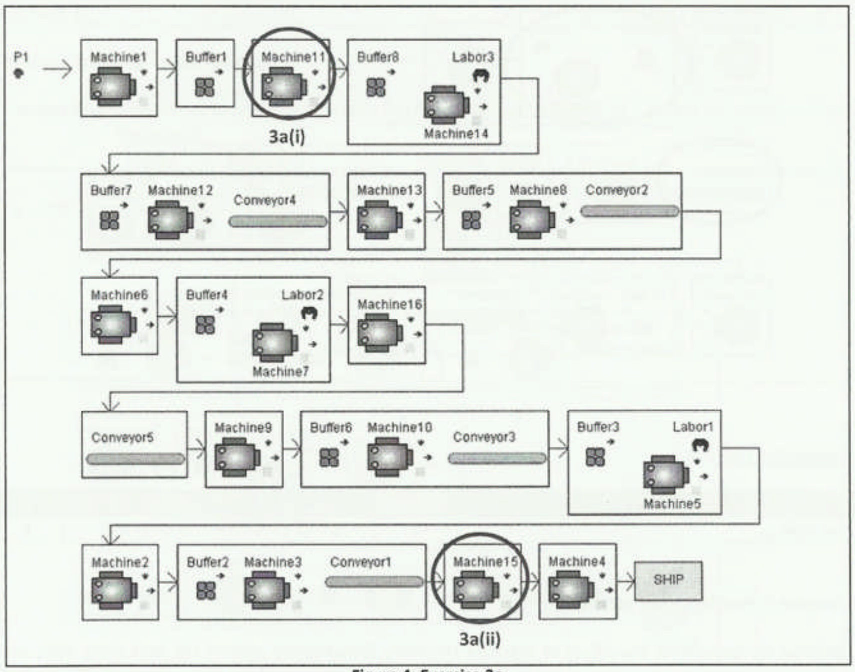

Figure 4: Exercise 3a

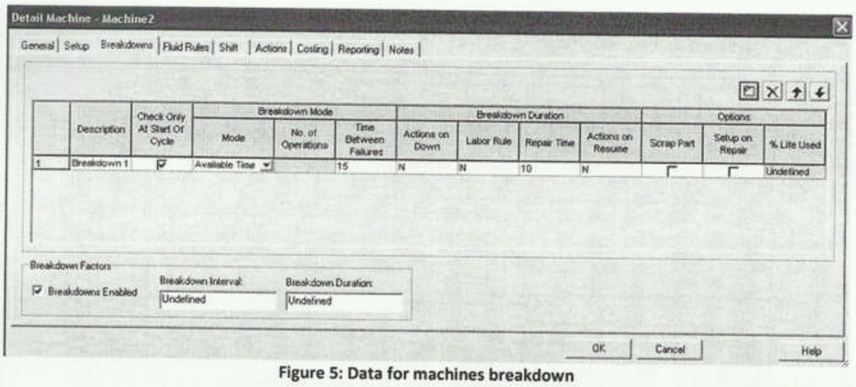

Figure 5: Data for machines breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

<u>Evaluation: Exercise 3(a)</u>

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

50%. can be completed & another 50%. is
a requires more ~~time~~ than
1 Hour to do it.

5

Exercise 3b: Comparing the effect of machine reliability (breakdown) for Machine16 as shown in Figure 6 based on two conditions:

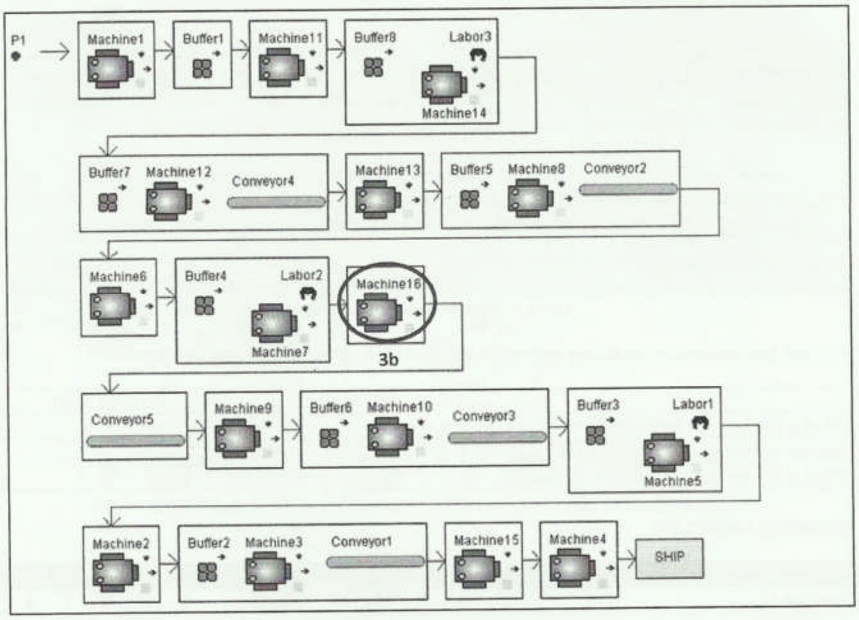

Figure 6: Exercise 3b

Table 2: Data for Exercise 3b

i. breakdown is often (short MTBF[1]) but repair time is quick (short MTTF[2])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[1] MTBF: Mean time between failures

[2] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

Exercise 3b(i)

- In order to include the breakdown in "Machine16", it is necessary to specify that breakdown will occur in the element details as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3b(ii)

- Change the details of breakdown as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

It requires more time, minimum more than 2 Hrs.

Sharanaba

Mode B: Building the model using prototype

Please follow the guidelines and instructions provided for each exercise.

Exercise 1: Building, linking and running a model (Normal Modelling)

Please build a model as shown on Figure 7. Linking all the elements and run the model. A part is delivered to SM1 and other elements as shown below.

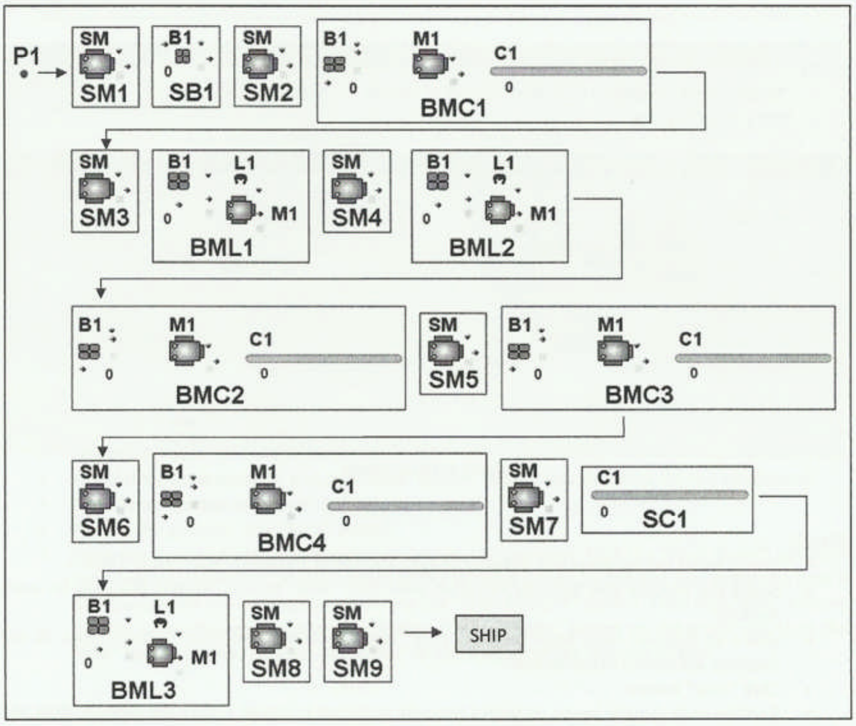

Figure 7: Layout

$2\frac{1}{2}$

Table 3: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Step 1:

- Please select "Assembly line" from the list of layouts as shown in Figure 8.
- Click "Next" button

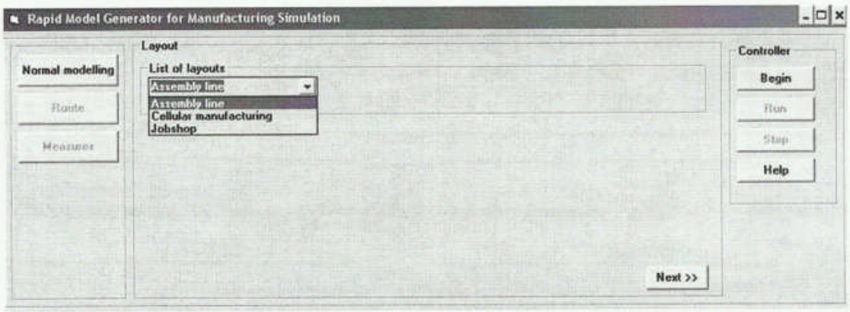

Figure 8: List of layout

Step 2:

- Please select the modules and quantity of each module as shown in Figure 9 and Table 4.
- Select the module and quantity required, then click "Add" button. Repeat this step for each module.
- When all modules have been selected, click "Begin" button, then "Run" button. Now, all the modules are shown in the screen.
- Click "Stop" button.
- Position each module based on layout required as shown in Figure 7. Click the module, drag and drop. Then, click "Next" button to link the elements (route for the part).

Table 4: Data for modules and its quantity

Module	Quantity
P (Part)	1
SM (Single machine)	9
SB (Single buffer)	1
SC (Single conveyor)	1
BMC (Buffer machine conveyor)	4
BML (Buffer machine labour)	3

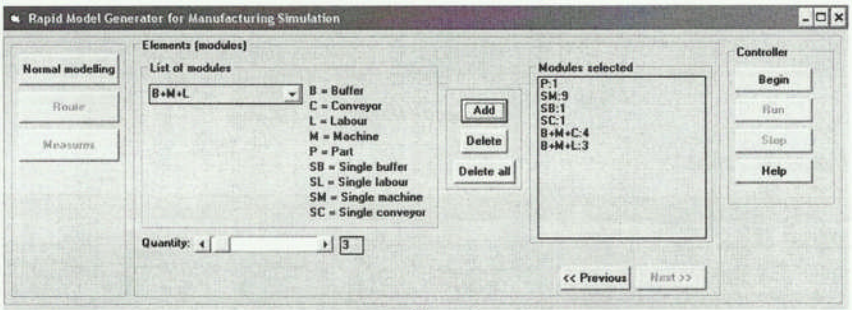

Figure 9: Modules and quantity

Step 3:

- Please add route for the part as shown in Figure 10.
- Select the first destination and click "Add" button. Repeat this step until the last destination.
- Click "Next" button and "Run" button.
- To stop the process, click "Stop" button
- Now, run the simulation model with run time at 480 unit time. Click the "Start RunAt" option on the "Execute Action Bar" at the bottom of the Witness screen. In the text box, enter the time as 480. Switch OFF the walk speed by clicking the "Walk ON/OFF" button. Then click "Run" button.
- To start again the simulation process at time 0, click "Begin" button on the prototype, then click "Run" button on the "Execute Action Bar" at the bottom of the Witness screen.

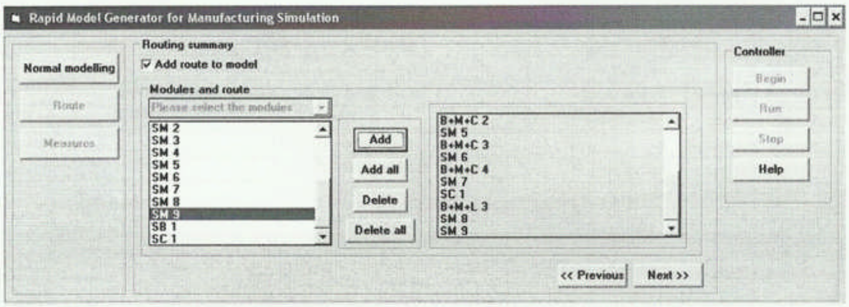

Figure 10: Routing

Evaluation: Exercise 1

	Difficult					Easy
Exercise 1	1	2	3	4	5	6 ✓

Exercise 2: Changing the routing (Route)

Exercise 2(a): Amend the previous model with the following layout (Figure 11). Link the modules and run the model.

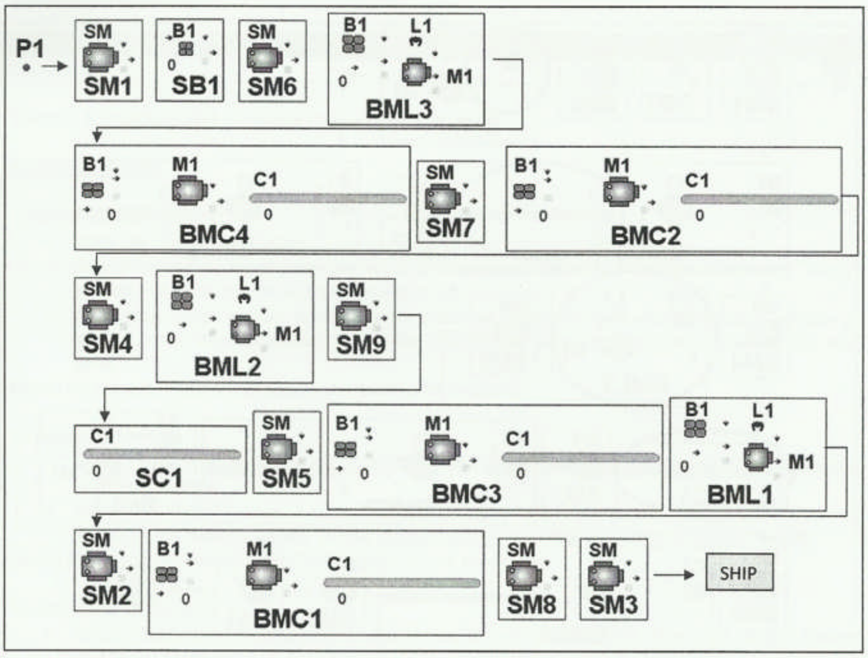

Figure 11: New layout

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 12.

Step 1:

- Click the "Route" button.
- The current route is shown in left panel. Click "Add all" button and the current route is now available in the right panel (New Route) as shown in Figure 13.
- On the "New Route" panel, select the element B1 in the "BML3" module, and click "Delete". Repeat this step for element C1 in module "BMC4". Then delete all elements in module "BML2" and module "SC1". Then click "Begin" button and "Run" button.

$1\frac{1}{2}$ minute.

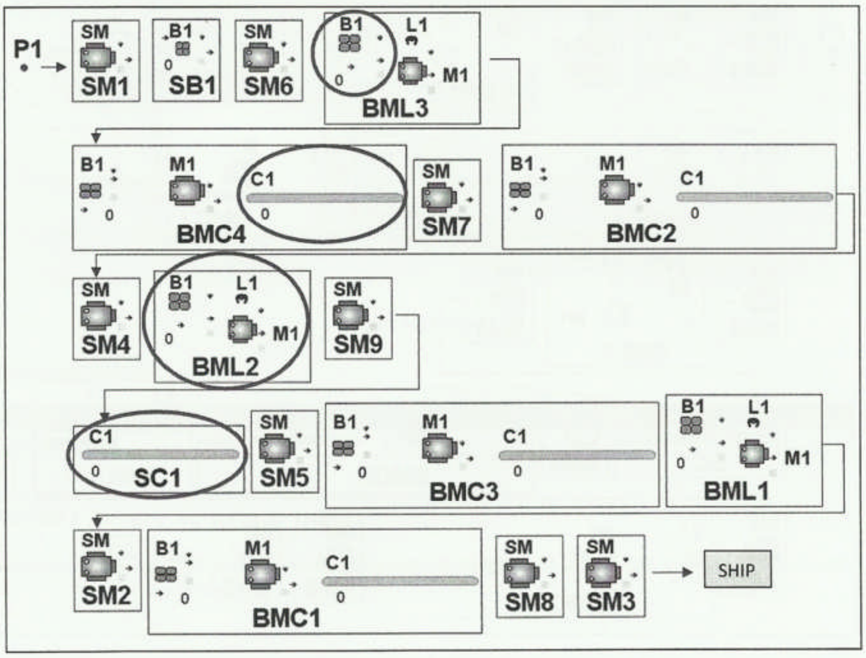

Figure 12: Changing the route

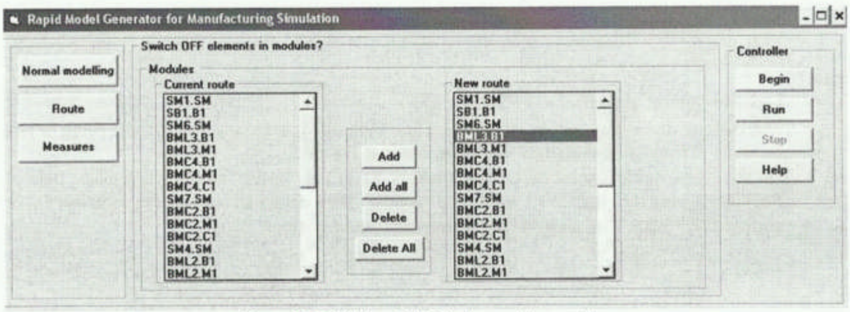

Figure 13: Switching ON/OFF elements in modules

1/2 minute.

13

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6 ✓

Exercise 3: Problems and measures (Measures)

General guidelines

To measure the lead time:

- Click the "Measures" button.
- Select "Long lead time" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button as shown in Figure 14.
- Now, click "Stop" button. A histogram is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the lead time.

(Note: Please use histogram to display the average of lead time).

To measure the WIP:

- Select "High WIP" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button.
- Now, click "Stop" button. A timeseries is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the WIP.

(Note: Please use timeseries to plot the number of WIP over time)

To detect the bottleneck:

- Select "Bottleneck" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button
- Now, click "Stop" button. Three pie charts are provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the machine utilisation.

(Note: Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

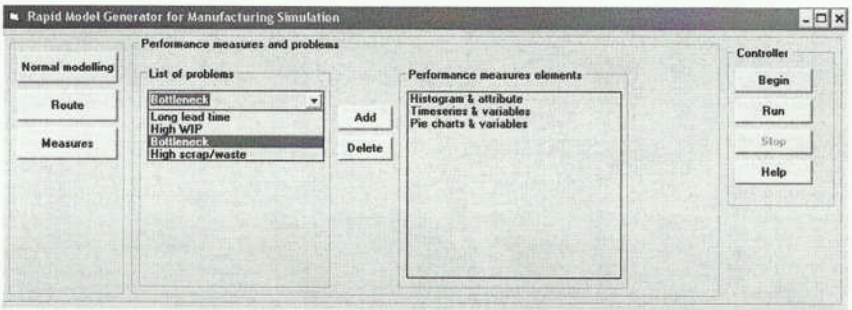

Figure 14: Measures

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 15.

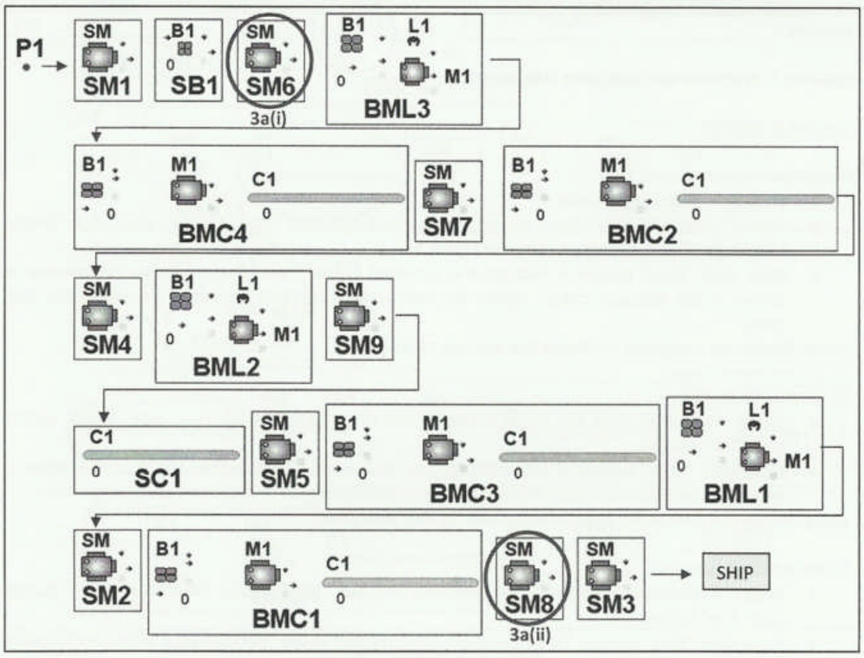

Figure 15: Exercise 3a

In order to include the breakdown in both machines, it is necessary to specify that breakdown will occur in the element (machine) details as shown in Figure 16.

Haminuty.

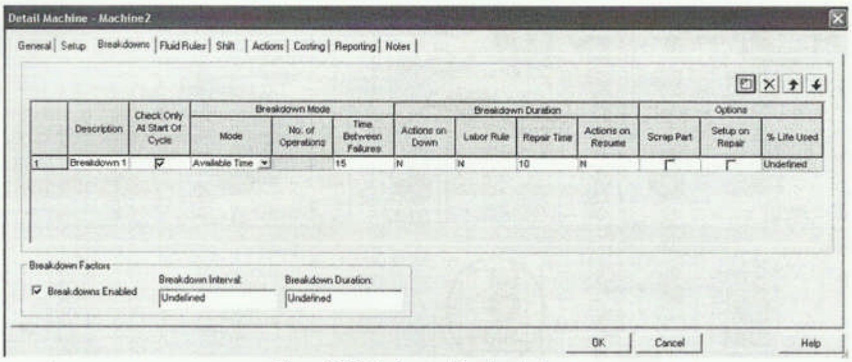

Figure 16: Data for machine breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?	90.40	
Number of WIP (work-in-progress)?	169	
What is the average of machine utilisation?		

Evaluation: Exercise 3(a)

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6 ✓

Exercise 3b: Comparing the effect of machine reliability (breakdown) for SM9 as shown in Figure 17 based on two conditions:

6 minutes

16

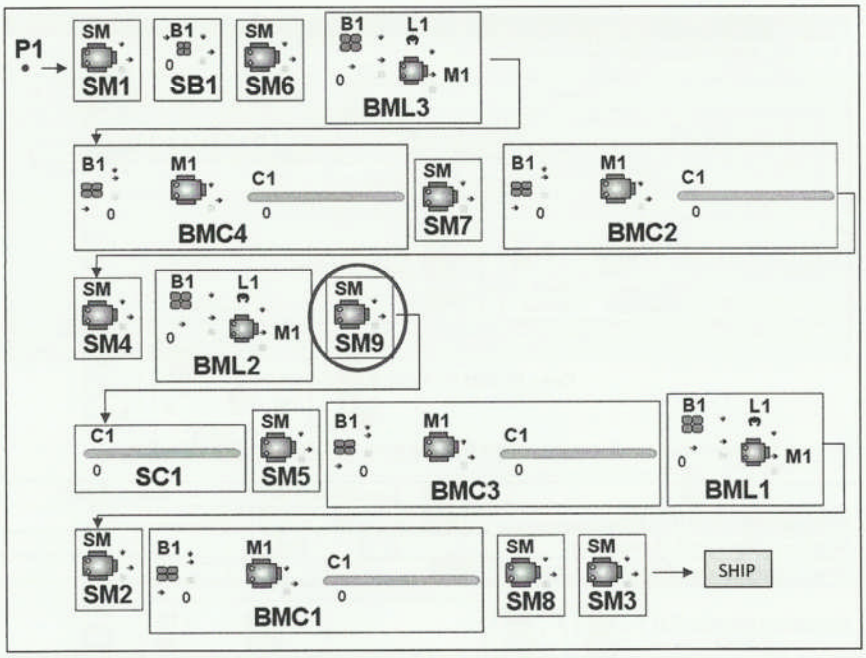

Figure 17: Exercise 3b

i. breakdown is often (short MTBF[3]) but repair time is quick (short MTTF[4])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[3] MTBF: Mean time between failures

[4] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5 ✓	6

$6\frac{1}{2}$ minutes.

The purpose of these questions is to measure to what extend this prototype can help the user to build the model. Please circle the number between 1 – 5, 1 being Strongly Disagree and 5 being Strongly Agree.

1. User experience

How long have you been involved in simulation and model building area?

Never	0 – 6 month	7 – 12 month	More than 12 month	No longer

2. Usage of Witness software (please tick)

During lectures only	
During group project	
During thesis project	
Before I came to Cranfield University	

3. Ease of use

	Strongly Disagree					Strongly Agree
The prototype is easy to use	1	2	3	4	5	6
The instructions are easy to read and understandable	1	2	3	4	5	6

4. Usefulness

	Strongly Disagree					Strongly Agree
The prototype will help me in model building	1	2	3	4	5	6
The prototype will help reduce time for model building	1	2	3	4	5	6
I can create the physical elements easily and faster	1	2	3	4	5	6
I can link the elements and run the model easily	1	2	3	4	5	6
I can switch ON/OFF any elements, link them again and run the model easily	1	2	3	4	5	6
I can easily measure the performance of the system (throughput rate, WIP, etc.)	1	2	3	4	5	6
All the elements provided for the performance measures are useful	1	2	3	4	5	6
The prototype has a lot of potential in improving model building	1	2	3	4	5	6
I will recommend this prototype to my colleagues	1	2	3	4	5	6

5. **Visual appearance**

	Strongly Disagree					Strongly Agree
The prototype displays visually pleasing design	1	2	3	4	5	6 ✓
Graphics and colour detract from actual content	1	2	3	4	5 ✓	6
The icons of the elements are easy to understand	1	2	3	4	5 ✓	6

6. **Comments/suggestions**

Witness Software is difficult to follow for the ~~..~~ new user. It needs some time to learn. ~~this~~ ~~..~~ It consumes more time for model building. This proto software can be easily understandable to the new user & it is user friendly. It will be very helpful for the user to learn very quickly

Appendix I Testing and validation results (Participant 5)

Monday 26/07/10

Abdul

Rapid Model Generator for Manufacturing Simulation

Aim: To investigate a new method to rapidly build simulation model based on classification of problems using cladistics technique and template approach.

This exercise is part of the study in developing a prototype referred to as "Rapid Model Generator" in simulation modelling. Your participation in this study will help us improve the design of the prototype.

We would appreciate if you could give us your true opinion and suggestions about the prototype. Please note that we are evaluating the prototype, NOT your performance in using the software. The intention is to measure to what extent the prototype can help the user build the model.

Mode A: Building a model manually

Exercise 1: Building, linking and running a model

Please build a model as shown on Figure 1. Linking all the elements and run the model. A part is delivered to Machine1 and other elements as shown below.

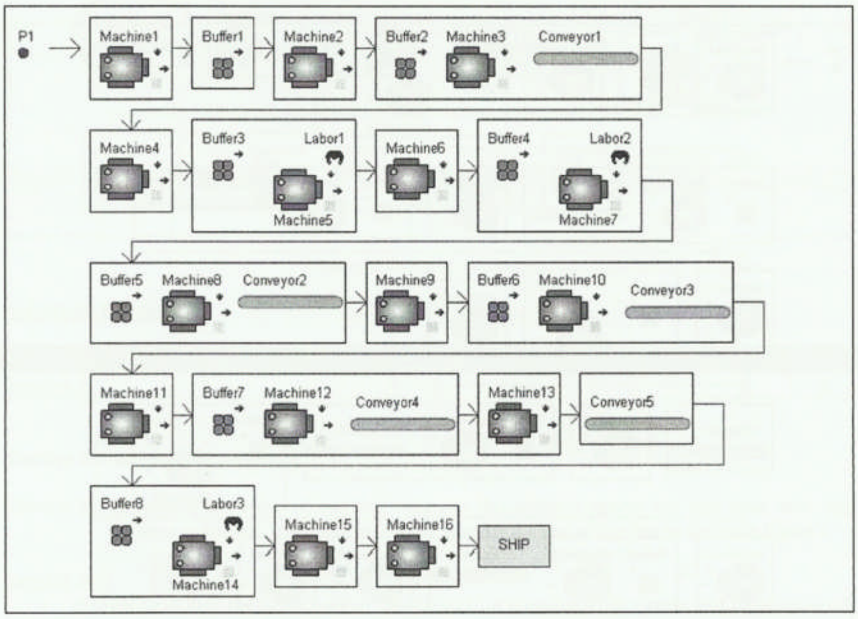

Figure 1: Layout

1

Table 1: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Evaluation: Exercise 1

	Difficult					Easy
Exercise 1	1	2	3	4	5	6

Exercise 2: Changing the routing

Exercise 2(a): Amend the previous model with the following layout (Figure 2). Link the elements and run the model.

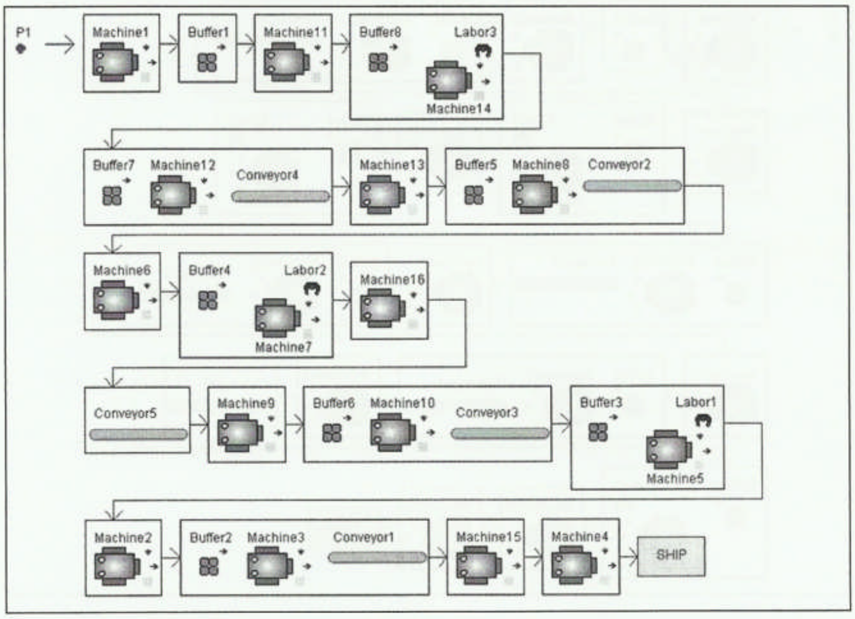

Figure 2: New layout

2

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 3.

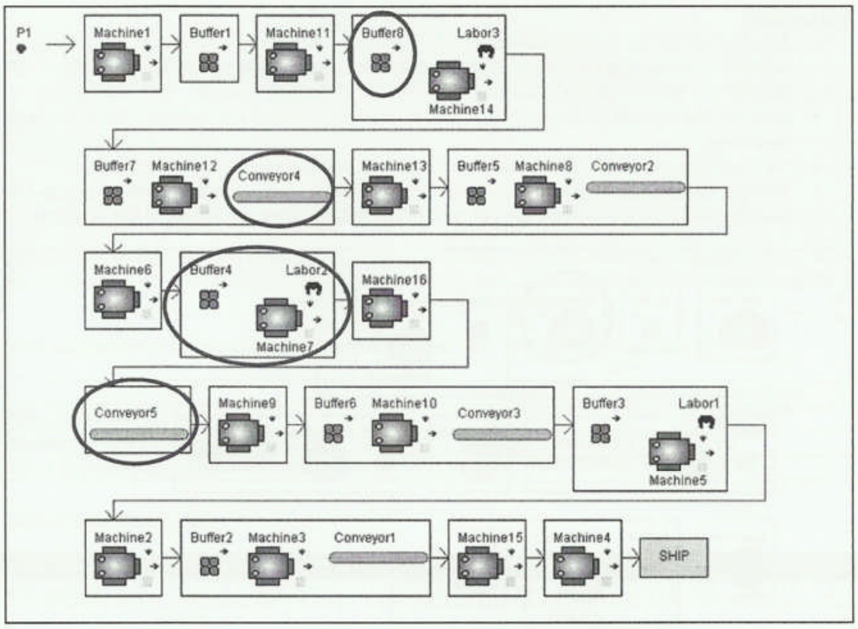

Figure 3: Changing the routing

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 4.

Exercise 3a(i)

- In order to include the breakdown in "Machine11", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).

- Find out the average of machine utilisation ("Machine11") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3a(ii)

- Delete the breakdown details in "Machine11".
- In order to include the breakdown in "Machine15", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine15") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

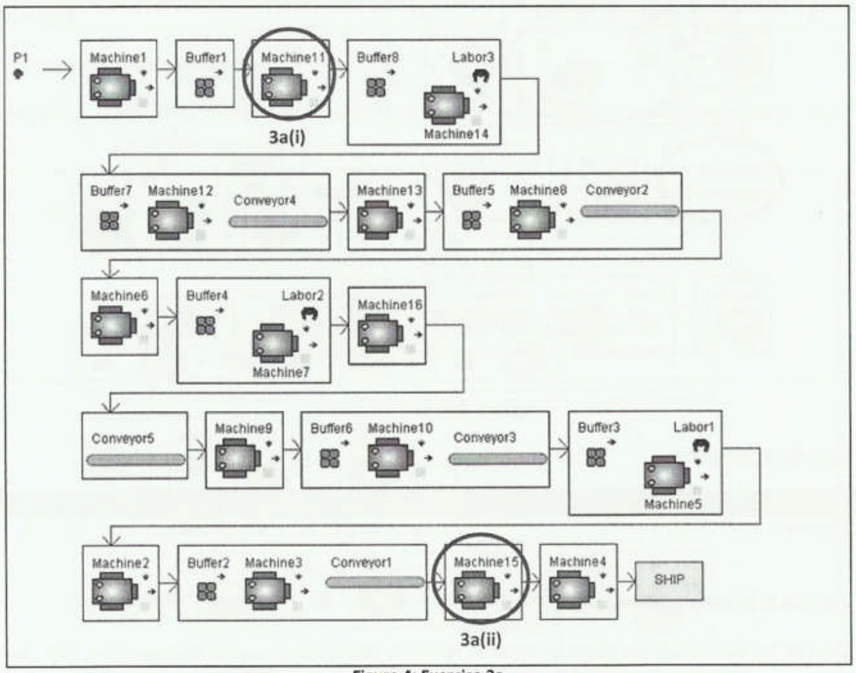

Figure 4: Exercise 3a

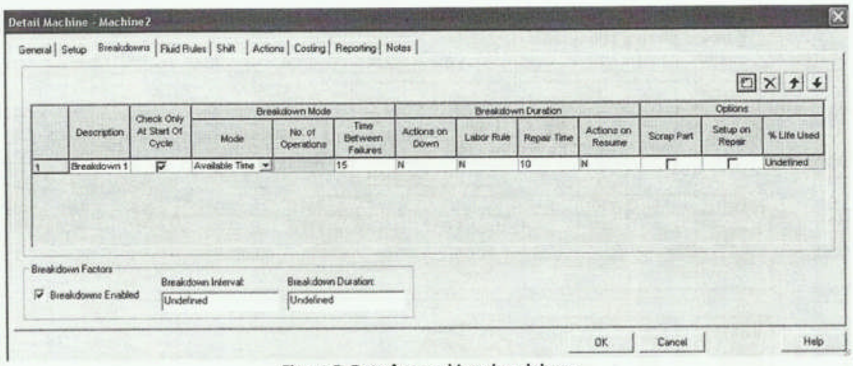

Figure 5: Data for machines breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?	X	X
Number of WIP (work-in-progress)?	X	X
What is the average of machine utilisation?	X	X

Evaluation: Exercise 3(a)

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

Exercise 3b: Comparing the effect of machine reliability (breakdown) for Machine16 as shown in Figure 6 based on two conditions:

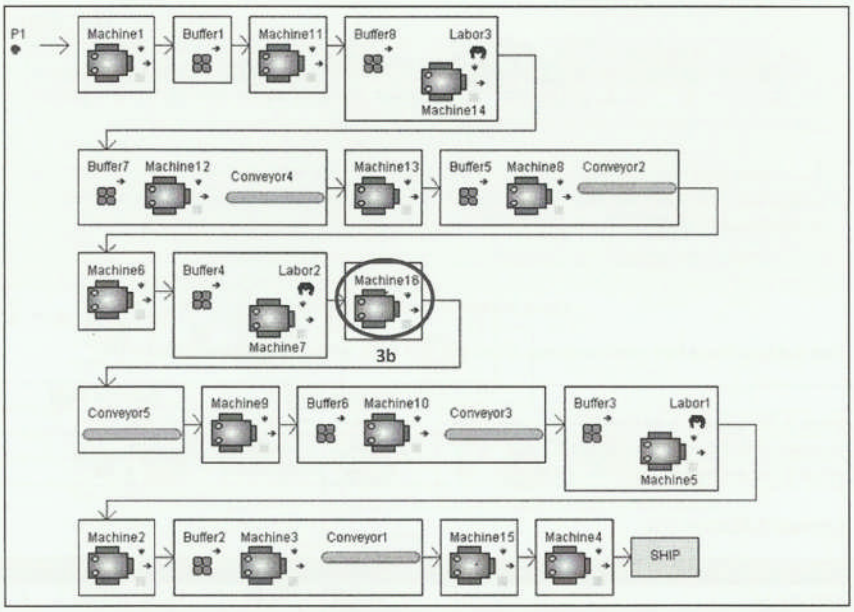

Figure 6: Exercise 3b

Table 2: Data for Exercise 3b

i. breakdown is often (short MTBF[1]) but repair time is quick (short MTTF[2])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[1] MTBF: Mean time between failures

[2] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

Exercise 3b(i)

- In order to include the breakdown in "Machine16", it is necessary to specify that breakdown will occur in the element details as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3b(ii)

- Change the details of breakdown as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?	X	X
Number of WIP (work-in-progress)?	X	X
What is the average of machine utilisation?	X	X

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

Abdul

Monday 26/07/10

Mode B: Building the model using prototype

Please follow the guidelines and instructions provided for each exercise.

Exercise 1: Building, linking and running a model (Normal Modelling)

Please build a model as shown on Figure 7. Linking all the elements and run the model. A part is delivered to SM1 and other elements as shown below.

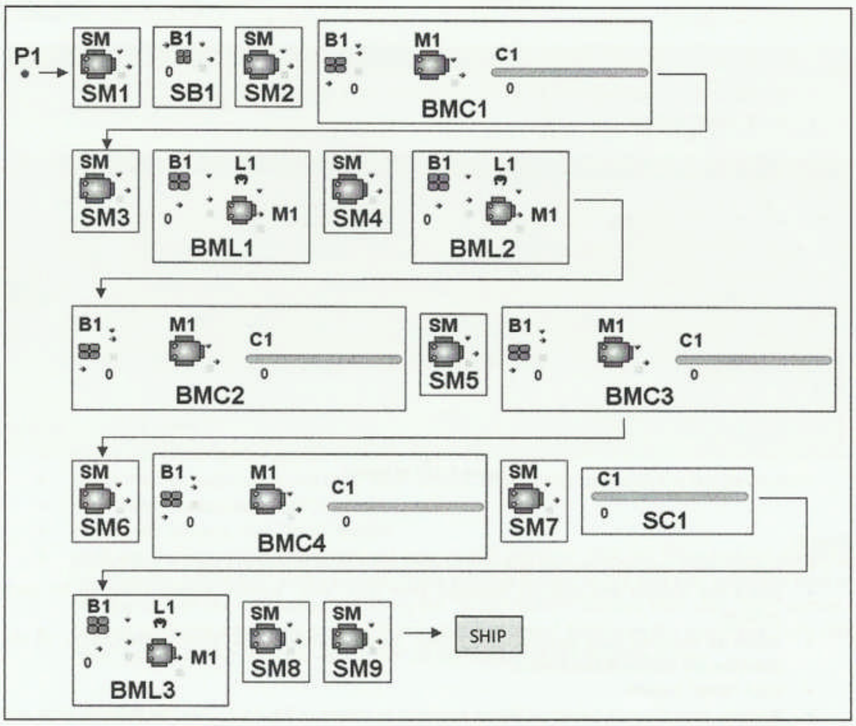

Figure 7: Layout

8

Table 3: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Step 1:

- Please select "Assembly line" from the list of layouts as shown in Figure 8.
- Click "Next" button

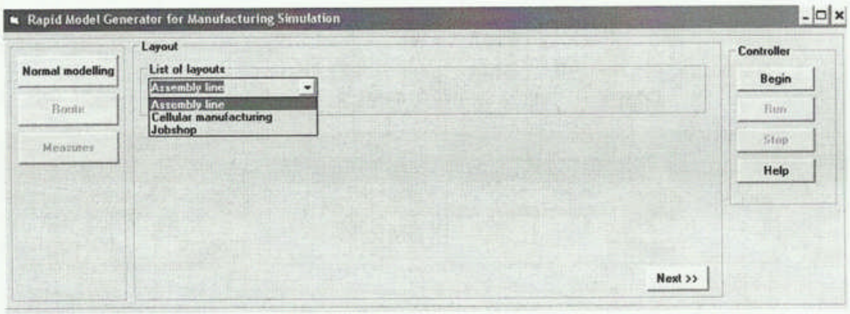

Figure 8: List of layout

Step 2:

- Please select the modules and quantity of each module as shown in Figure 9 and Table 4.
- Select the module and quantity required, then click "Add" button. Repeat this step for each module.
- When all modules have been selected, click "Begin" button, then "Run" button. Now, all the modules are shown in the screen.
- Click "Stop" button.
- Position each module based on layout required as shown in Figure 7. Click the module, drag and drop. Then, click "Next" button to link the elements (route for the part).

Table 4: Data for modules and its quantity

Module	Quantity
P (Part)	1
SM (Single machine)	9
SB (Single buffer)	1
SC (Single conveyor)	1
BMC (Buffer machine conveyor)	4
BML (Buffer machine labour)	3

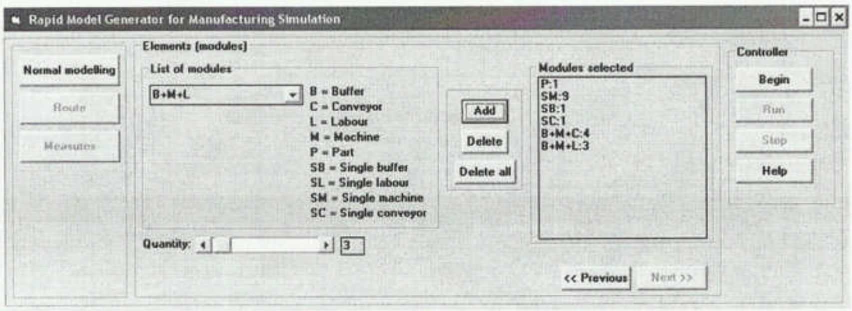

Figure 9: Modules and quantity

Step 3:

- Please add route for the part as shown in Figure 10.
- Select the first destination and click "Add" button. Repeat this step until the last destination.
- Click "Next" button and "Run" button.
- To stop the process, click "Stop" button
- Now, run the simulation model with run time at 480 unit time. Click the "Start RunAt" option on the "Execute Action Bar" at the bottom of the Witness screen. In the text box, enter the time as 480. Switch OFF the walk speed by clicking the "Walk ON/OFF" button. Then click "Run" button.
- To start again the simulation process at time 0, click "Begin" button on the prototype, then click "Run" button on the "Execute Action Bar" at the bottom of the Witness screen.

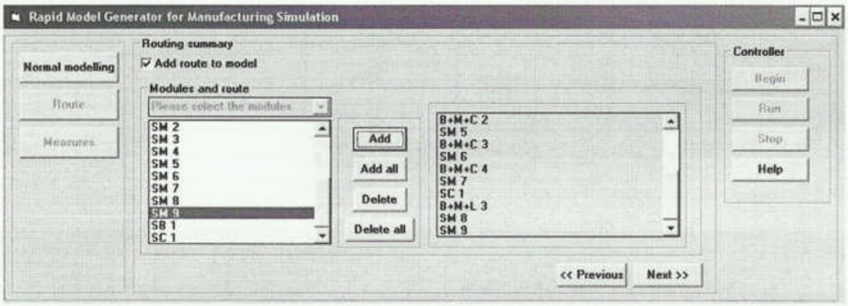

Figure 10: Routing

<u>Evaluation: Exercise 1</u>

	Difficult					Easy
Exercise 1	1	2	3	4	5	6

Exercise 2: Changing the routing (Route)

Exercise 2(a): Amend the previous model with the following layout (Figure 11). Link the modules and run the model.

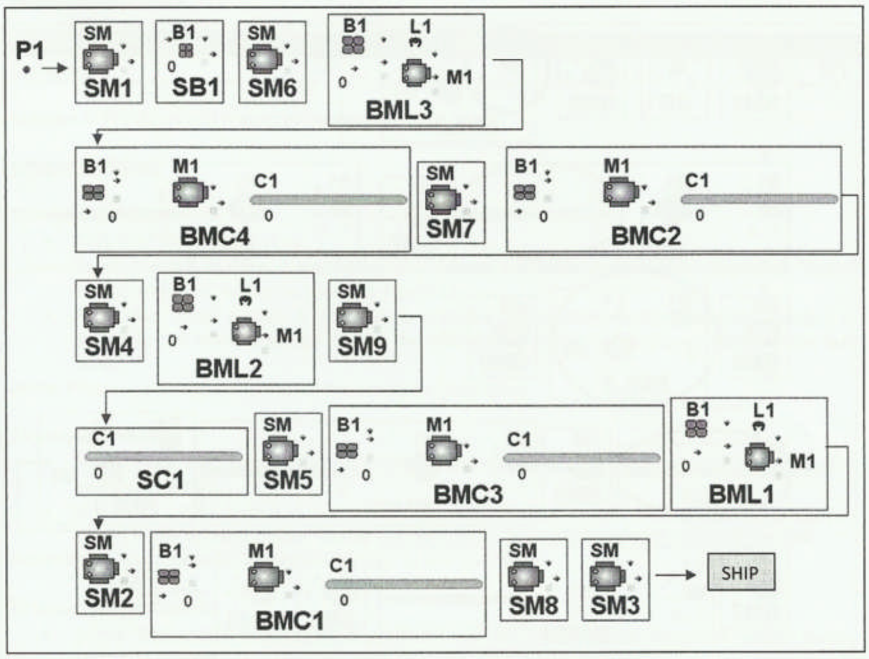

Figure 11: New layout

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 12.

Step 1:

- Click the "Route" button.
- The current route is shown in left panel. Click "Add all" button and the current route is now available in the right panel (New Route) as shown in Figure 13.
- On the "New Route" panel, select the element B1 in the "BML3" module, and click "Delete". Repeat this step for element C1 in module "BMC4". Then delete all elements in module "BML2" and module "SC1". Then click "Begin" button and "Run" button.

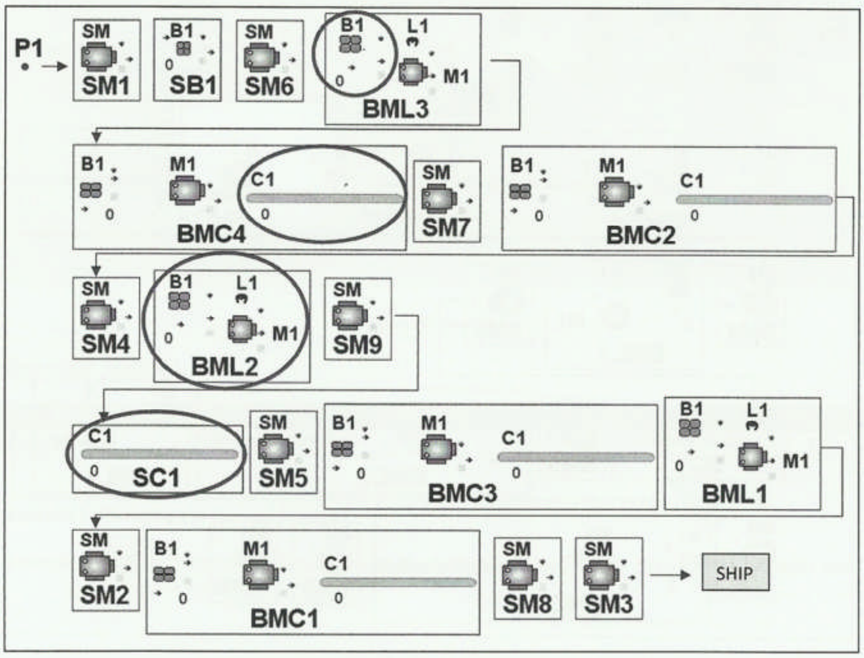

Figure 12: Changing the route

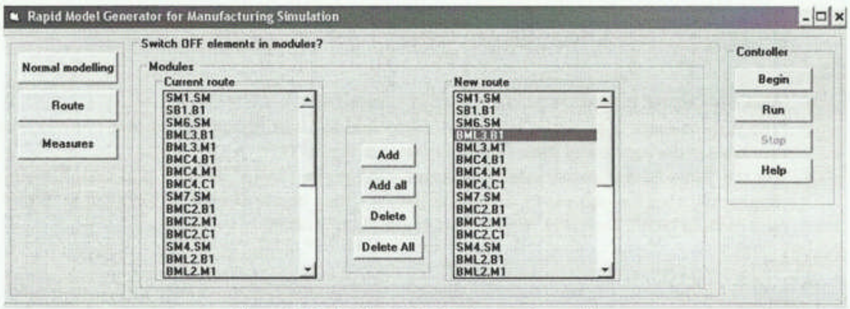

Figure 13: Switching ON/OFF elements in modules

13

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures (Measures)

General guidelines

To measure the lead time:

- Click the "Measures" button.
- Select "Long lead time" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button as shown in Figure 14.
- Now, click "Stop" button. A histogram is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the lead time.

(Note: Please use histogram to display the average of lead time).

To measure the WIP:

- Select "High WIP" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button.
- Now, click "Stop" button. A timeseries is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the WIP.

(Note: Please use timeseries to plot the number of WIP over time)

To detect the bottleneck:

- Select "Bottleneck" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button
- Now, click "Stop" button. Three pie charts are provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the machine utilisation.

(Note: Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

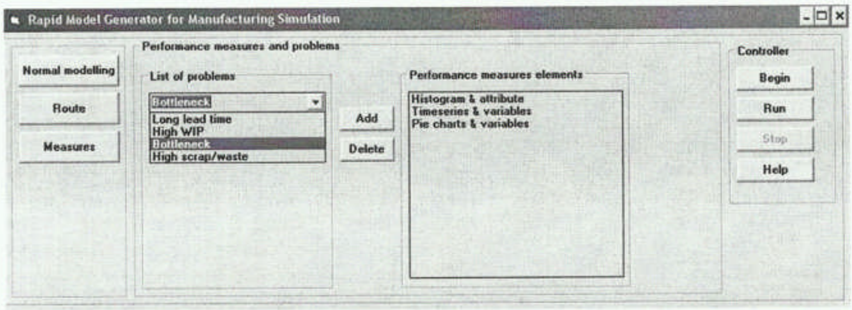

Figure 14: Measures

14

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 15.

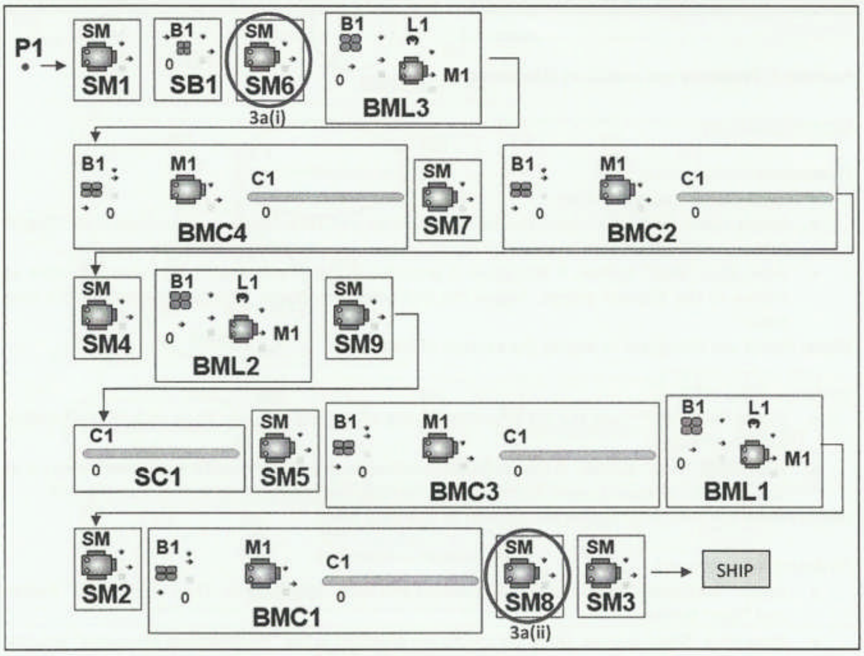

Figure 15: Exercise 3a

In order to include the breakdown in both machines, it is necessary to specify that breakdown will occur in the element (machine) details as shown in Figure 16.

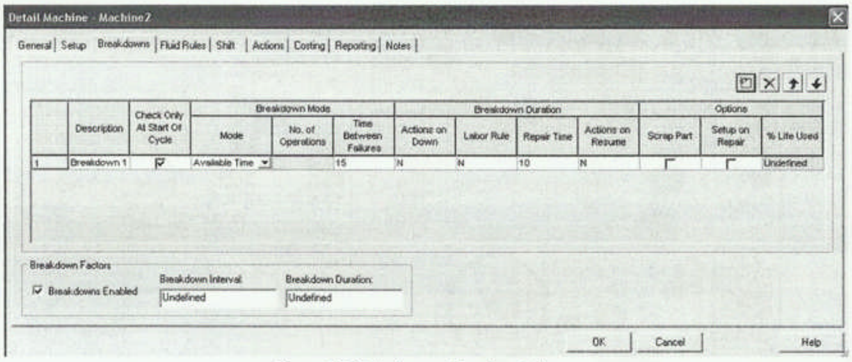

Figure 16: Data for machine breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?	90.40	96.31
Number of WIP (work-in-progress)?	169 tput 312	175 tput 306
What is the average of machine utilisation?	33.62	31.87

Evaluation: Exercise 3(a)

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

Exercise 3b: Comparing the effect of machine reliability (breakdown) for SM9 as shown in Figure 17 based on two conditions:

16

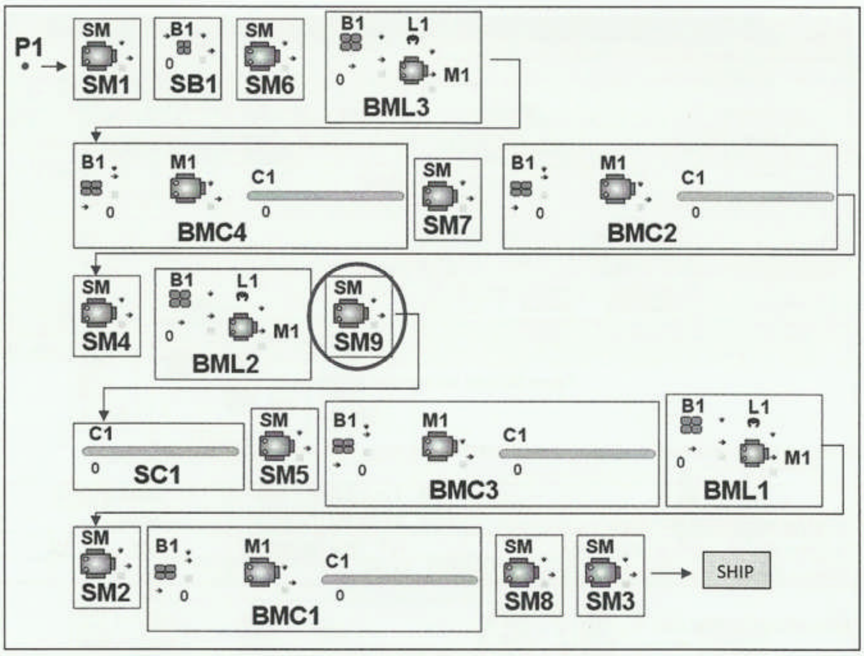

Figure 17: Exercise 3b

i. breakdown is often (short MTBF[3]) but repair time is quick (short MTTF[4])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[3] MTBF: Mean time between failures

[4] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?	20.28	191.93
Number of WIP (work-in-progress)?	20 total 461	401 total 80
What is the average of machine utilisation?	48.21	8.33

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

The purpose of these questions is to measure to what extend this prototype can help the user to build the model. Please circle the number between 1 – 5, 1 being Strongly Disagree and 5 being Strongly Agree.

1. **User experience**

How long have you been involved in simulation and model building area?

Never	0 – 6 month	7 – 12 month	More than 12 month	No longer
	✓			

2. **Usage of Witness software (please tick)**

During lectures only	
During group project	
During thesis project	✓
Before I came to Cranfield University	

3. **Ease of use**

	Strongly Disagree					Strongly Agree
The prototype is easy to use	1	2	3	4	5	6
The instructions are easy to read and understandable	1	2	3	4	5	6

4. **Usefulness**

	Strongly Disagree					Strongly Agree
The prototype will help me in model building	1	2	3	4	5	6
The prototype will help reduce time for model building	1	2	3	4	5	6
I can create the physical elements easily and faster	1	2	3	4	5	6
I can link the elements and run the model easily	1	2	3	4	5	6
I can switch ON/OFF any elements, link them again and run the model easily	1	2	3	4	5	6
I can easily measure the performance of the system (throughput rate, WIP, etc.)	1	2	3	4	5	6
All the elements provided for the performance measures are useful	1	2	3	4	5	6
The prototype has a lot of potential in improving model building	1	2	3	4	5	6
I will recommend this prototype to my colleagues	1	2	3	4	5	6

19

Abdul

5. **Visual appearance**

	Strongly Disagree					Strongly Agree
The prototype displays visually pleasing design	1	2	3	4	5	6
Graphics and colour detract from actual content	1	2	3	4	5	6
The icons of the elements are easy to understand	1	2	3	4	5	6

6. **Comments/suggestions**

Appendix J Testing and validation results (Participant 6)

Kate

Rapid Model Generator for Manufacturing Simulation

Aim: To investigate a new method to rapidly build simulation model based on classification of problems using cladistics technique and template approach.

This exercise is part of the study in developing a prototype referred to as "Rapid Model Generator" in simulation modelling. Your participation in this study will help us improve the design of the prototype.

We would appreciate if you could give us your true opinion and suggestions about the prototype. Please note that we are evaluating the prototype, NOT your performance in using the software. The intention is to measure to what extent the prototype can help the user build the model.

Mode A: Building a model manually

Exercise 1: Building, linking and running a model

Please build a model as shown on Figure 1. Linking all the elements and run the model. A part is delivered to Machine1 and other elements as shown below.

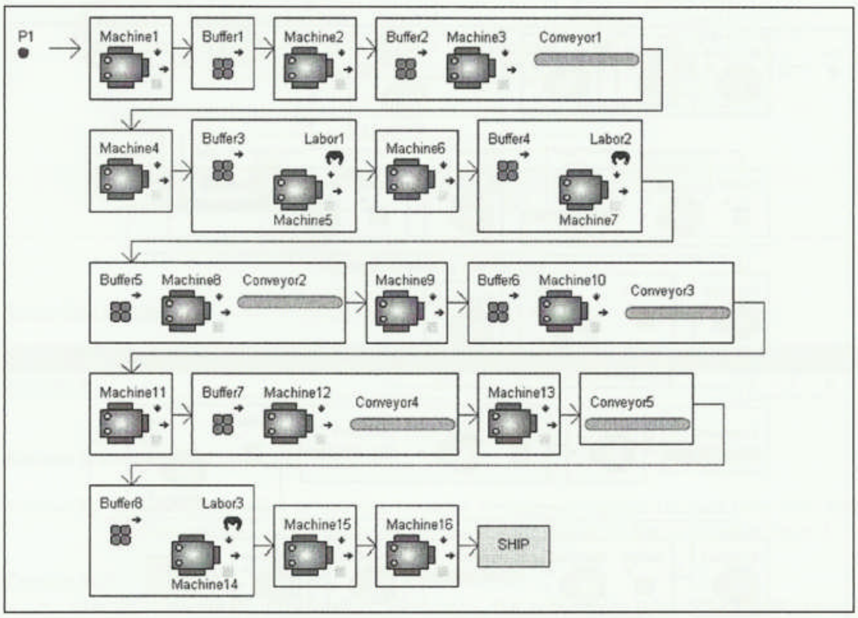

Figure 1: Layout

1

Table 1: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Evaluation: Exercise 1

	Difficult					Easy
Exercise 1	1	2	3	4	5	6

Tiny consumption 1

Exercise 2: Changing the routing

Exercise 2(a): Amend the previous model with the following layout (Figure 2). Link the elements and run the model.

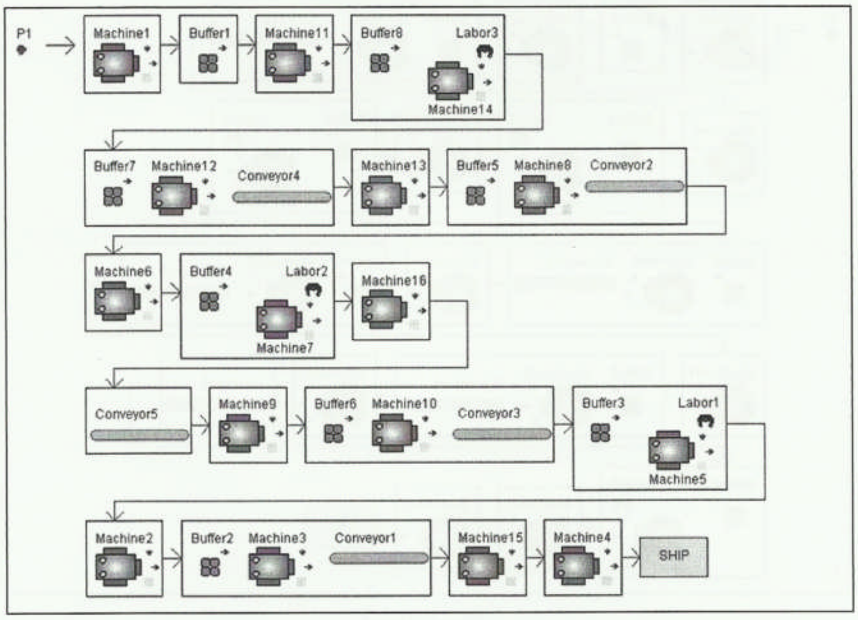

Figure 2: New layout

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 3.

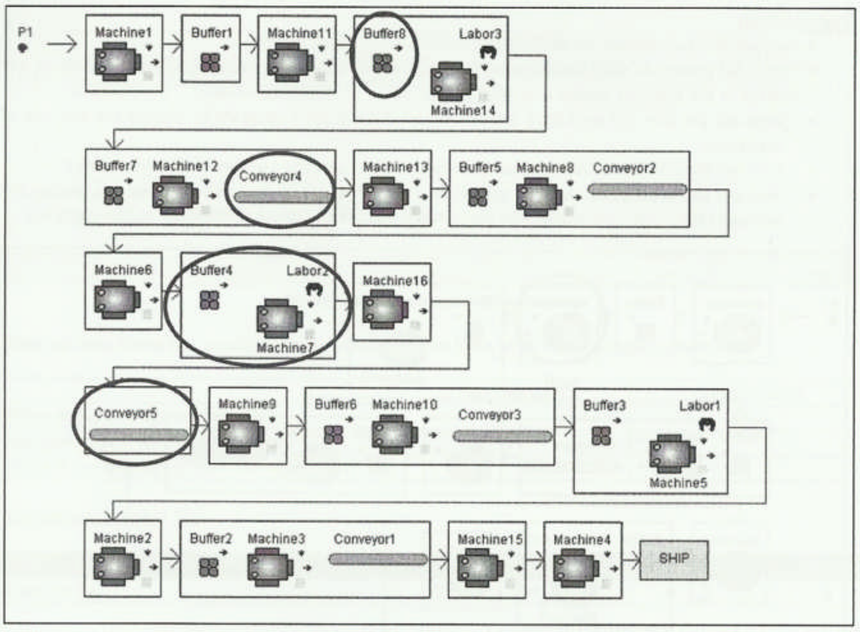

Figure 3: Changing the routing

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 4.

Exercise 3a(i)

- In order to include the breakdown in "Machine11", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).

- Find out the average of machine utilisation ("Machine11") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

<u>Exercise 3a(ii)</u>

- Delete the breakdown details in "Machine11".
- In order to include the breakdown in "Machine15", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine15") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

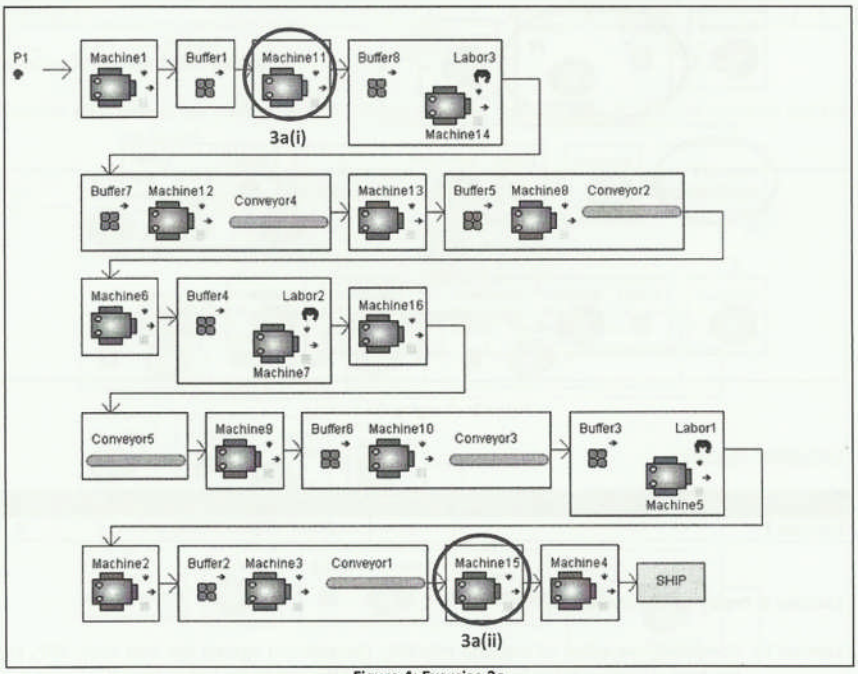

Figure 4: Exercise 3a

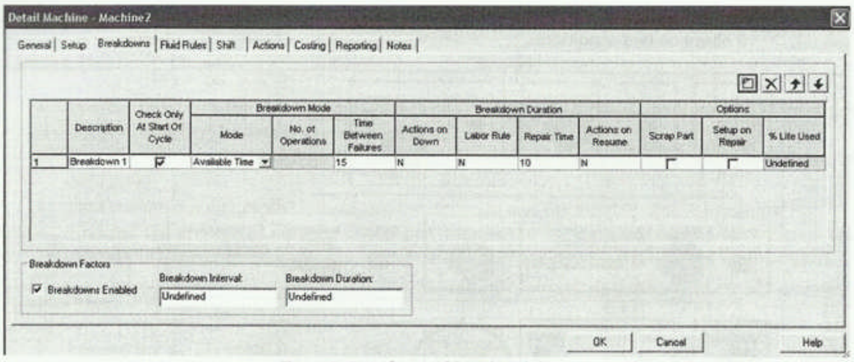

Figure 5: Data for machines breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

Evaluation: Exercise 3(a)

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

Exercise omit due to the lack of practice with the tool.
Considered as difficulty 5. applicable for both 3a &b.

5

Exercise 3b: Comparing the effect of machine reliability (breakdown) for Machine16 as shown in Figure 6 based on two conditions:

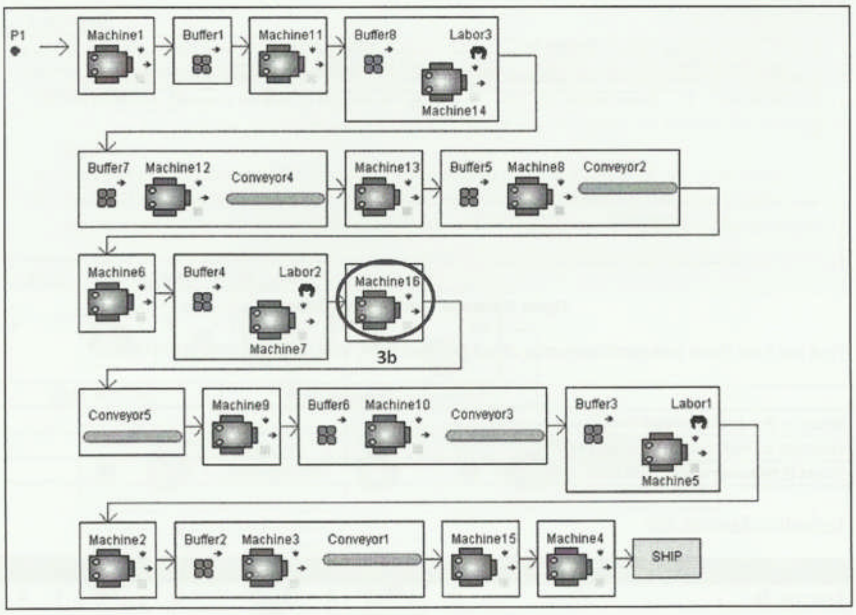

Figure 6: Exercise 3b

Table 2: Data for Exercise 3b

i. breakdown is often (short MTBF[1]) but repair time is quick (short MTTF[2])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[1] MTBF: Mean time between failures

[2] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

Exercise 3b(i)

- In order to include the breakdown in "Machine16", it is necessary to specify that breakdown will occur in the element details as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3b(ii)

- Change the details of breakdown as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

Mode B: Building the model using prototype

Please follow the guidelines and instructions provided for each exercise.

Exercise 1: Building, linking and running a model (Normal Modelling)

Please build a model as shown on Figure 7. Linking all the elements and run the model. A part is delivered to SM1 and other elements as shown below.

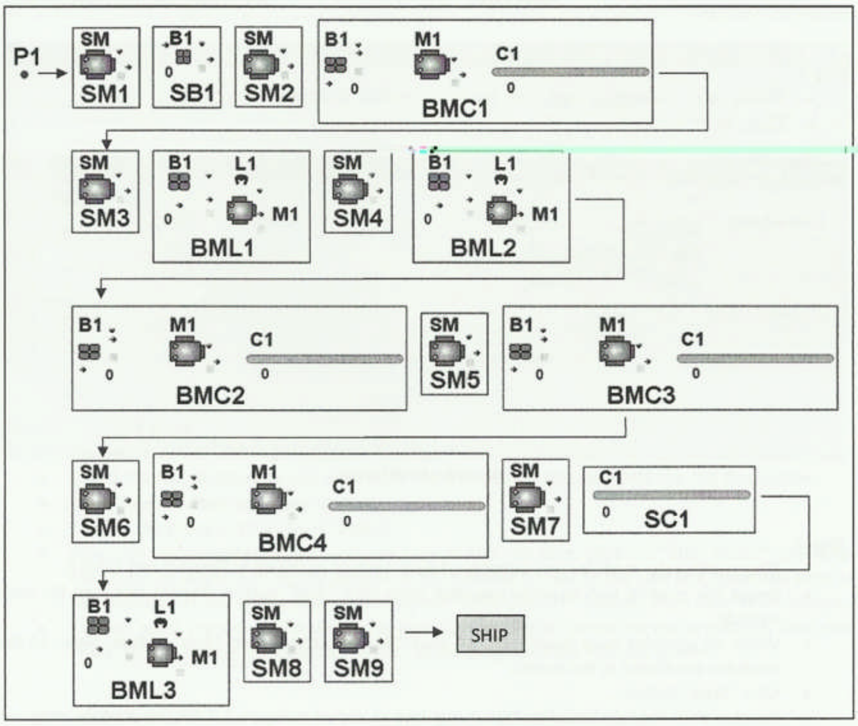

Figure 7: Layout

Table 3: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Step 1:

- Please select "Assembly line" from the list of layouts as shown in Figure 8.
- Click "Next" button

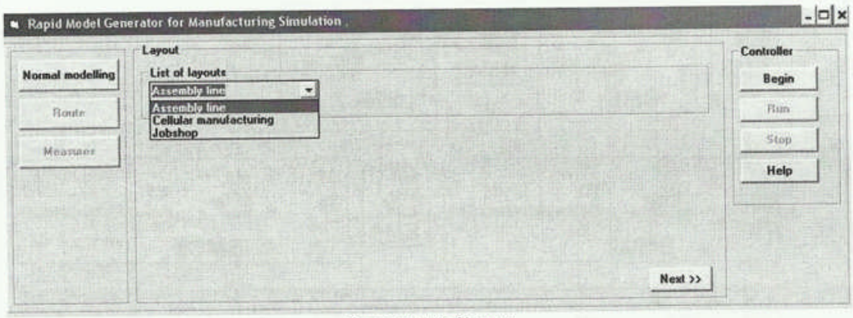

Figure 8: List of layout

Step 2:

- Please select the modules and quantity of each module as shown in Figure 9 and Table 4.
- Select the module and quantity required, then click "Add" button. Repeat this step for each module.
- When all modules have been selected, click "Begin" button, then "Run" button. Now, all the modules are shown in the screen.
- Click "Stop" button.
- Position each module based on layout required as shown in Figure 7. Click the module, drag and drop. Then, click "Next" button to link the elements (route for the part).

Table 4: Data for modules and its quantity

Module	Quantity
P (Part)	1
SM (Single machine)	9
SB (Single buffer)	1
SC (Single conveyor)	1
BMC (Buffer machine conveyor)	4
BML (Buffer machine labour)	3

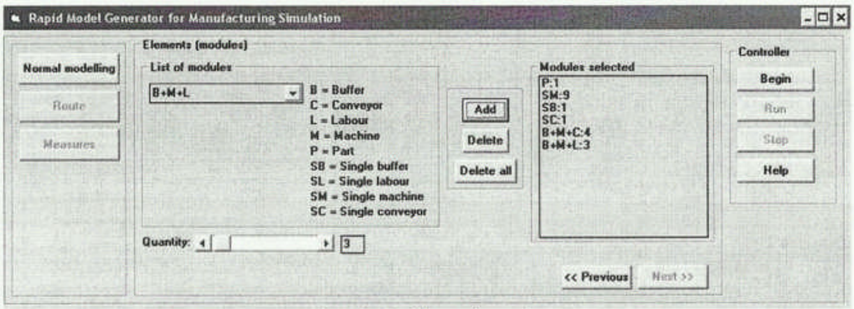

Figure 9: Modules and quantity

Step 3:

- Please add route for the part as shown in Figure 10.
- Select the first destination and click "Add" button. Repeat this step until the last destination.
- Click "Next" button and "Run" button.
- To stop the process, click "Stop" button
- Now, run the simulation model with run time at 480 unit time. Click the "Start RunAt" option on the "Execute Action Bar" at the bottom of the Witness screen. In the text box, enter the time as 480. Switch OFF the walk speed by clicking the "Walk ON/OFF" button. Then click "Run" button.
- To start again the simulation process at time 0, click "Begin" button on the prototype, then click "Run" button on the "Execute Action Bar" at the bottom of the Witness screen.

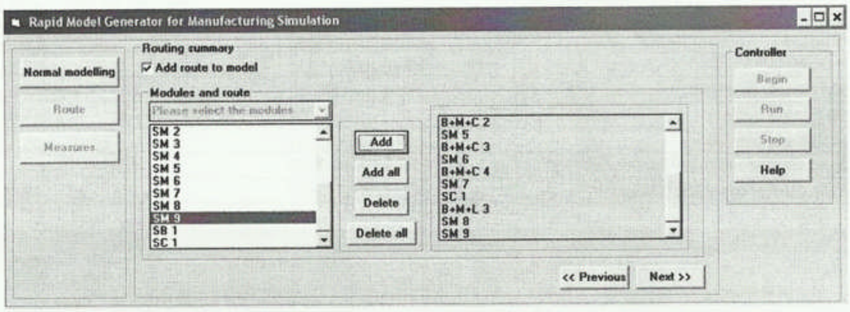

Figure 10: Routing

Evaluation: Exercise 1

	Difficult					Easy
Exercise 1	1	2	3	4	5	6

Less time consuming

Exercise 2: Changing the routing (Route)

Exercise 2(a): Amend the previous model with the following layout (Figure 11). Link the modules and run the model.

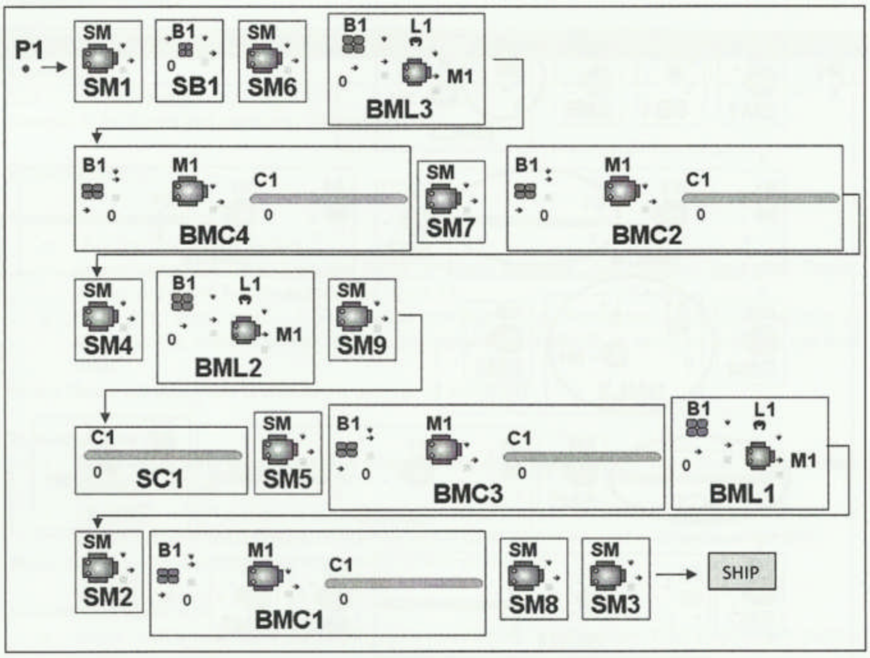

Figure 11: New layout

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 12.

Step 1:

- Click the "Route" button.
- The current route is shown in left panel. Click "Add all" button and the current route is now available in the right panel (New Route) as shown in Figure 13.
- On the "New Route" panel, select the element B1 in the "BML3" module, and click "Delete". Repeat this step for element C1 in module "BMC4". Then delete all elements in module "BML2" and module "SC1". Then click "Begin" button and "Run" button.

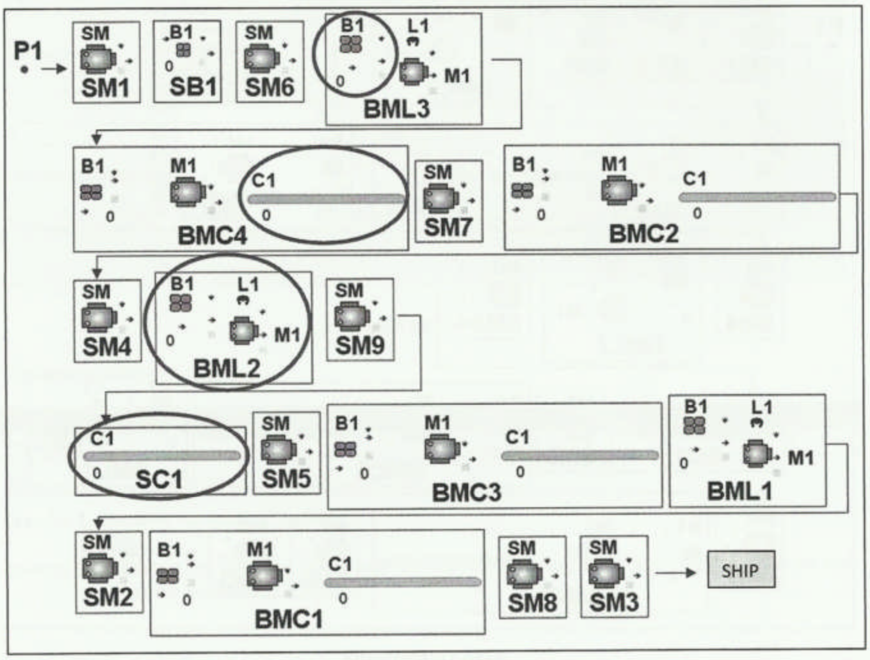

Figure 12: Changing the route

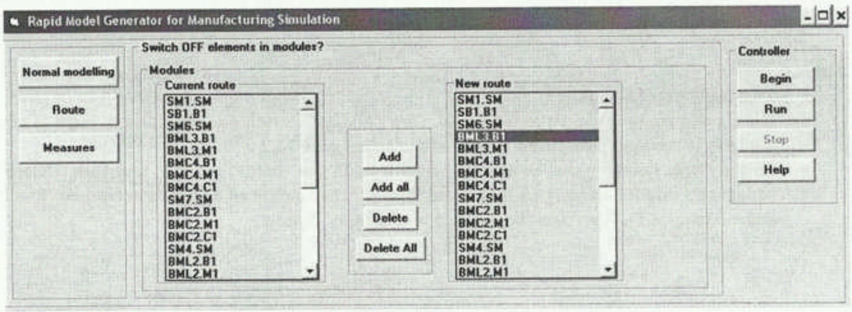

Figure 13: Switching ON/OFF elements in modules

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Tool is unstable. - prototype.

Exercise 3: Problems and measures (Measures)

General guidelines

To measure the lead time:

- Click the "Measures" button.
- Select "Long lead time" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button as shown in Figure 14.
- Now, click "Stop" button. A histogram is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the lead time.

(Note: Please use histogram to display the average of lead time).

To measure the WIP:

- Select "High WIP" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button.
- Now, click "Stop" button. A timeseries is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the WIP.

(Note: Please use timeseries to plot the number of WIP over time)

To detect the bottleneck:

- Select "Bottleneck" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button
- Now, click "Stop" button. Three pie charts are provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the machine utilisation.

(Note: Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

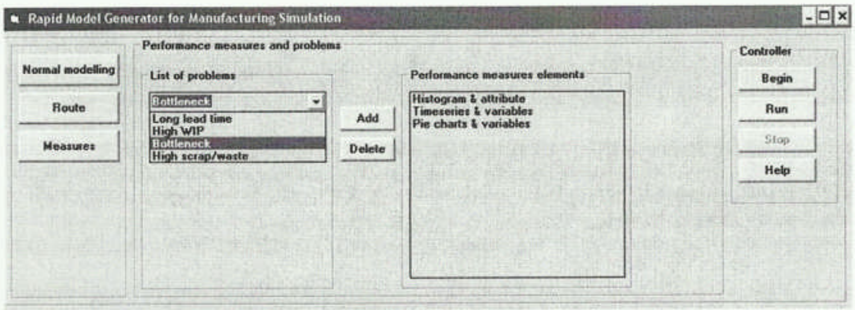

Figure 14: Measures

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 15.

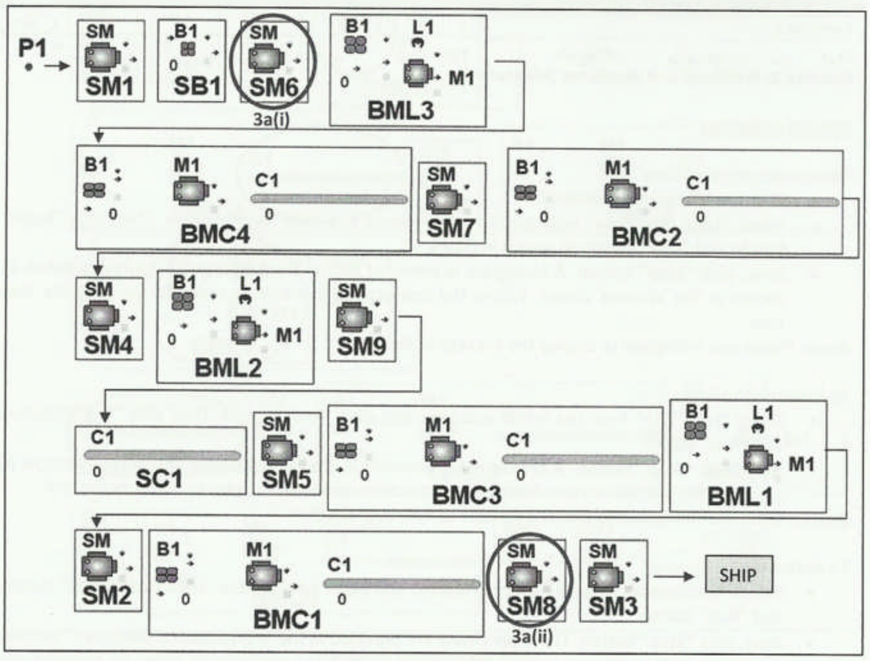

Figure 15: Exercise 3a

In order to include the breakdown in both machines, it is necessary to specify that breakdown will occur in the element (machine) details as shown in Figure 16.

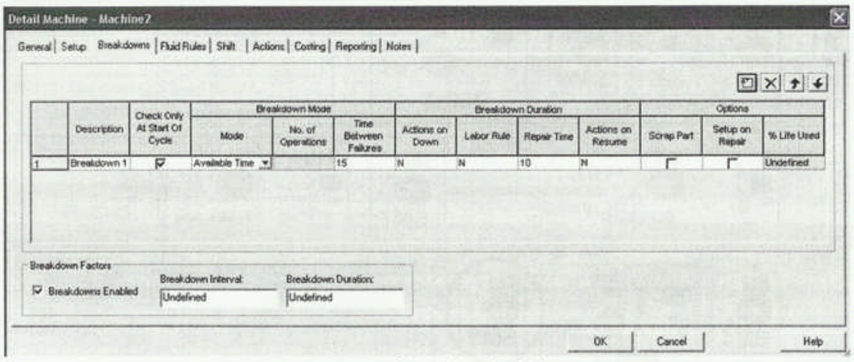

Figure 16: Data for machine breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?	90.4	96.31
Number of WIP (work-in-progress)?	169	175
What is the average of machine utilisation?	33.02%	31.87%

Evaluation: Exercise 3(a)

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

Exercise 3b: Comparing the effect of machine reliability (breakdown) for SM9 as shown in Figure 17 based on two conditions:

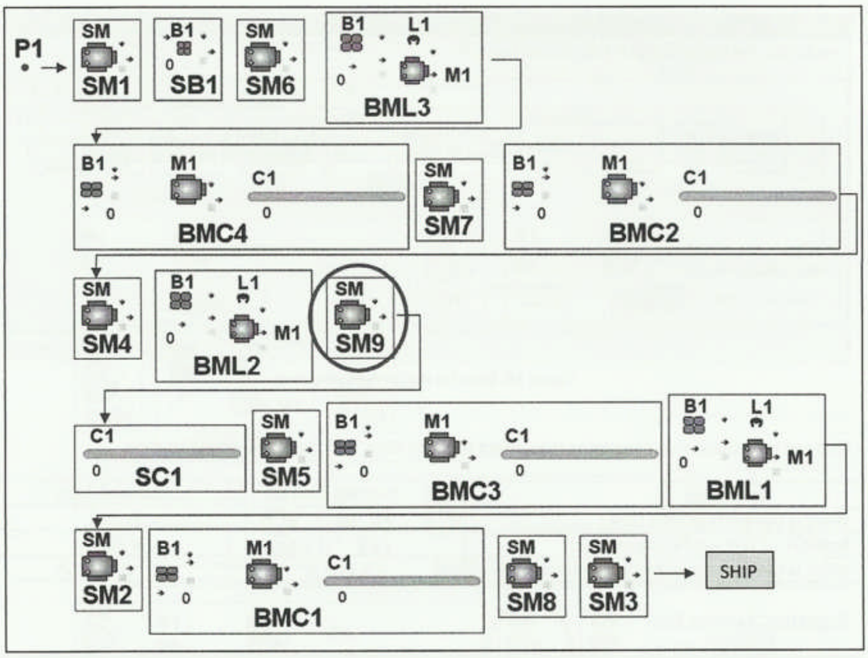

Figure 17: Exercise 3b

i. breakdown is often (short MTBF[3]) but repair time is quick (short MTTF[4])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[3] MTBF: Mean time between failures

[4] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?	20.28	191.23
Number of WIP (work-in-progress)?	20	401
What is the average of machine utilisation?	48.21 %	8.33%

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

The purpose of these questions is to measure to what extend this prototype can help the user to build the model. Please circle the number between 1 – 5, 1 being Strongly Disagree and 5 being Strongly Agree.

1. User experience

How long have you been involved in simulation and model building area?

Never	0 – 6 month	7 – 12 month	More than 12 month	No longer
			X	

Past work

2. Usage of Witness software (please tick)

During lectures only	
During group project	X
During thesis project	
Before I came to Cranfield University	

3. Ease of use

	Strongly Disagree					Strongly Agree
The prototype is easy to use	1	2	3	4	5	6
The instructions are easy to read and understandable	1	2	3	4	5	6

4. Usefulness

	Strongly Disagree					Strongly Agree
The prototype will help me in model building	1	2	3	4	5	6
The prototype will help reduce time for model building	1	2	3	4	5	6
I can create the physical elements easily and faster	1	2	3	4	5	6
I can link the elements and run the model easily	1	2	3	4	5	6
I can switch ON/OFF any elements, link them again and run the model easily	1	2	3	4	5	6
I can easily measure the performance of the system (throughput rate, WIP, etc.)	1	2	3	4	5	6
All the elements provided for the performance measures are useful	1	2	3	4	5	6
The prototype has a lot of potential in improving model building	1	2	3	4	5	6
I will recommend this prototype to my colleagues	1	2	3	4	5	6

19

5. **Visual appearance**

	Strongly Disagree					Strongly Agree
The prototype displays visually pleasing design	1	2	3	4	5	6
Graphics and colour detract from actual content	1	2	3	4	5	6
The icons of the elements are easy to understand	1	2	3	4	5	6

6. **Comments/suggestions**

Some clarification in instruction is recommended

Appendix K Testing and validation results (Participant 7)

Kevin 17/8/10

Rapid Model Generator for Manufacturing Simulation

Aim: To investigate a new method to rapidly build simulation model based on classification of problems using cladistics technique and template approach.

This exercise is part of the study in developing a prototype referred to as "Rapid Model Generator" in simulation modelling. Your participation in this study will help us improve the design of the prototype.

We would appreciate if you could give us your true opinion and suggestions about the prototype. Please note that we are evaluating the prototype, NOT your performance in using the software. The intention is to measure to what extent the prototype can help the user build the model.

Mode A: Building a model manually

Exercise 1: Building, linking and running a model

Please build a model as shown on Figure 1. Linking all the elements and run the model. A part is delivered to Machine1 and other elements as shown below.

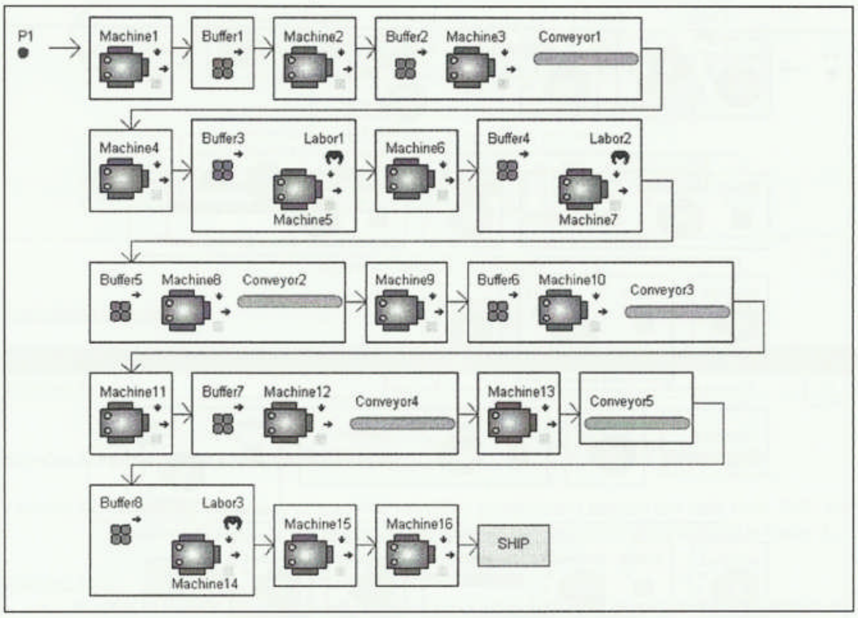

Figure 1: Layout

1

Table 1: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Evaluation: Exercise 1

	Difficult					Easy
Exercise 1	1	2	3	4	5	6

Exercise 2: Changing the routing

Exercise 2(a): Amend the previous model with the following layout (Figure 2). Link the elements and run the model.

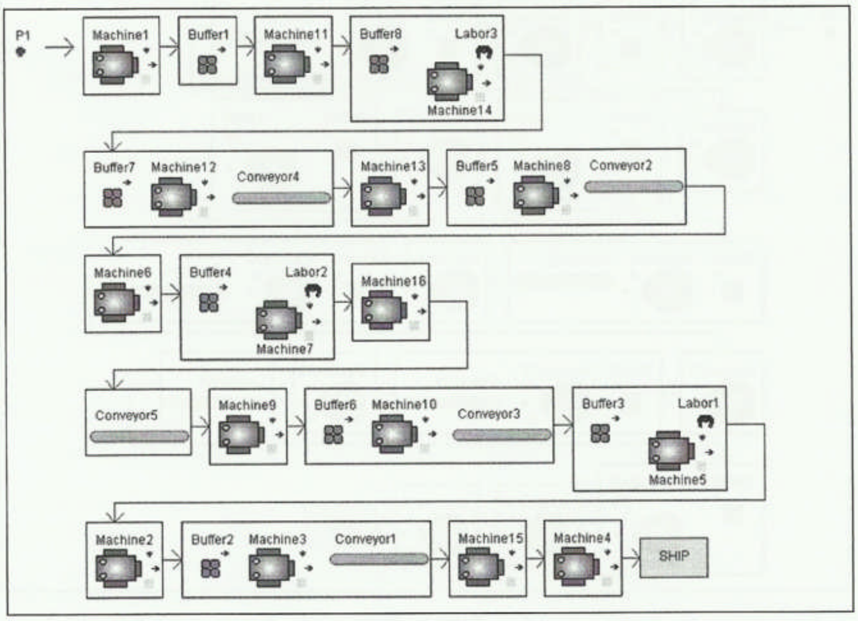

Figure 2: New layout

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 3.

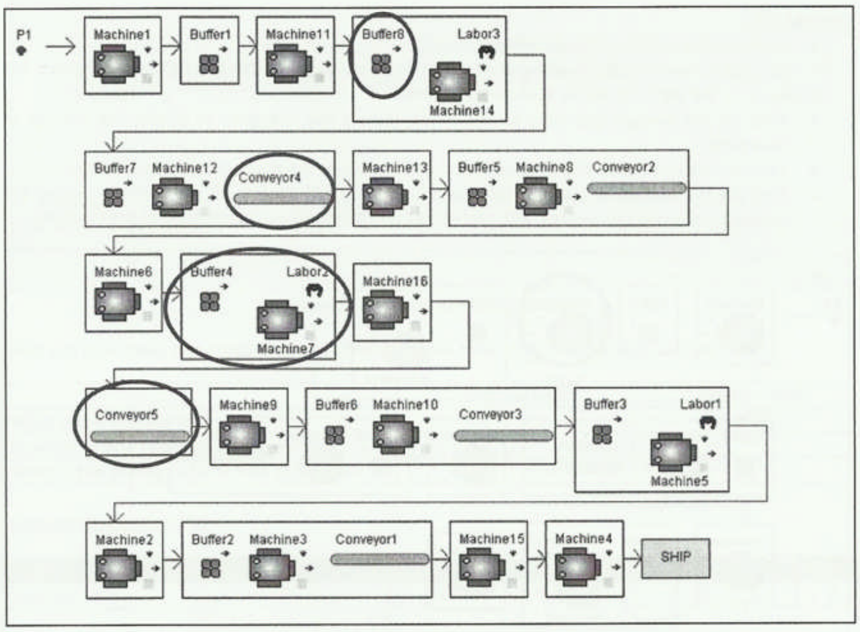

Figure 3: Changing the routing

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 4.

Exercise 3a(i)

- In order to include the breakdown in "Machine11", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).

- Find out the average of machine utilisation ("Machine11") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3a(ii)

- Delete the breakdown details in "Machine11".
- In order to include the breakdown in "Machine15", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine15") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

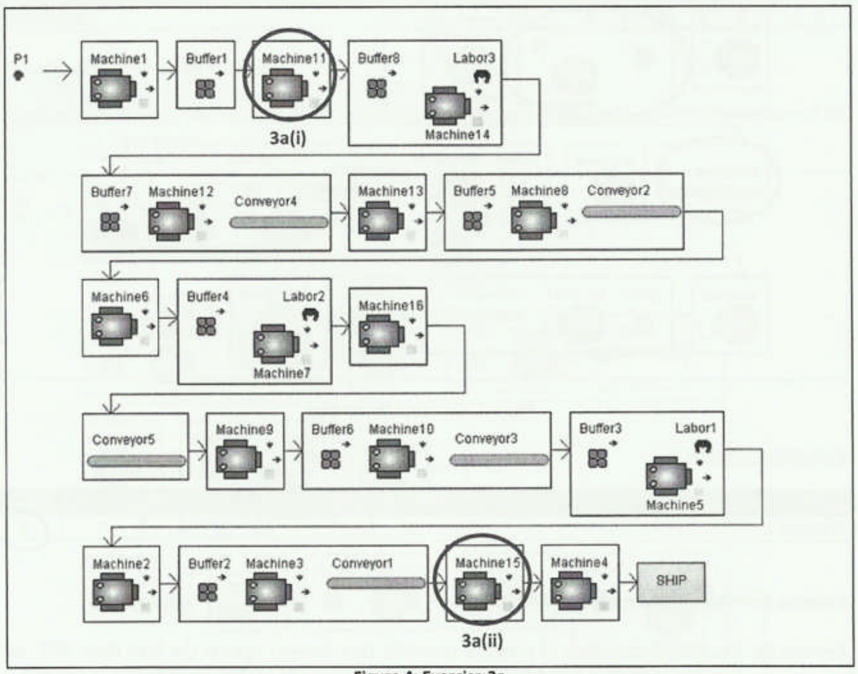

Figure 4: Exercise 3a

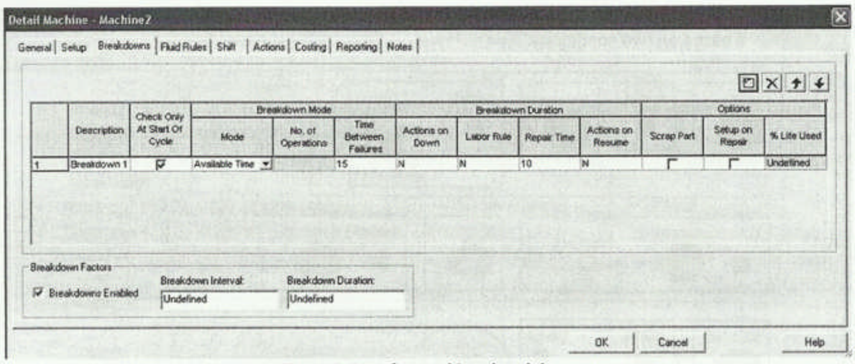

Figure 5: Data for machines breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

Evaluation: Exercise 3(a)

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

Exercise 3b: Comparing the effect of machine reliability (breakdown) for Machine16 as shown in Figure 6 based on two conditions:

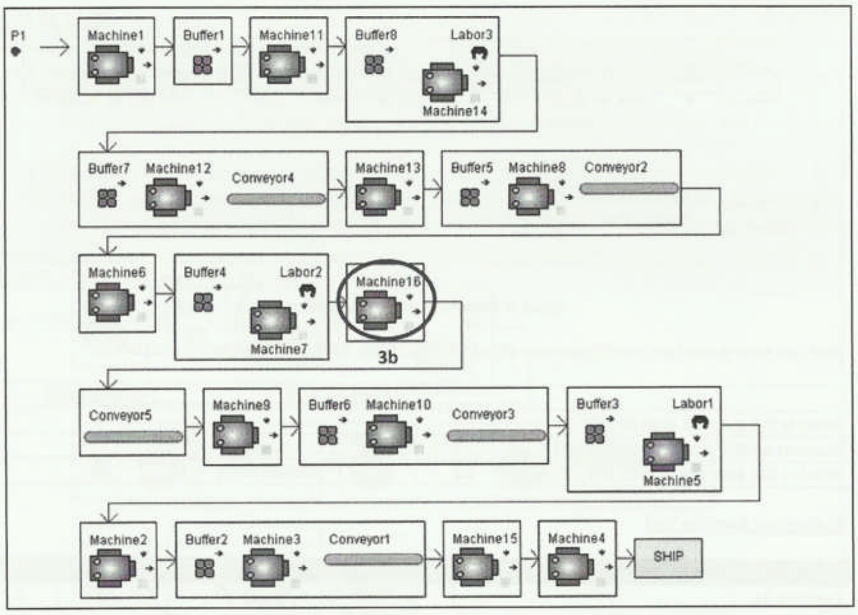

Figure 6: Exercise 3b

Table 2: Data for Exercise 3b

i. breakdown is often (short MTBF[1]) but repair time is quick (short MTTF[2])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[1] MTBF: Mean time between failures

[2] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

Exercise 3b(i)

- In order to include the breakdown in "Machine16", it is necessary to specify that breakdown will occur in the element details as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3b(ii)

- Change the details of breakdown as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

Kevin 17/8/10

Mode B: Building the model using prototype

Please follow the guidelines and instructions provided for each exercise.

Exercise 1: Building, linking and running a model (Normal Modelling)

Please build a model as shown on Figure 7. Linking all the elements and run the model. A part is delivered to SM1 and other elements as shown below.

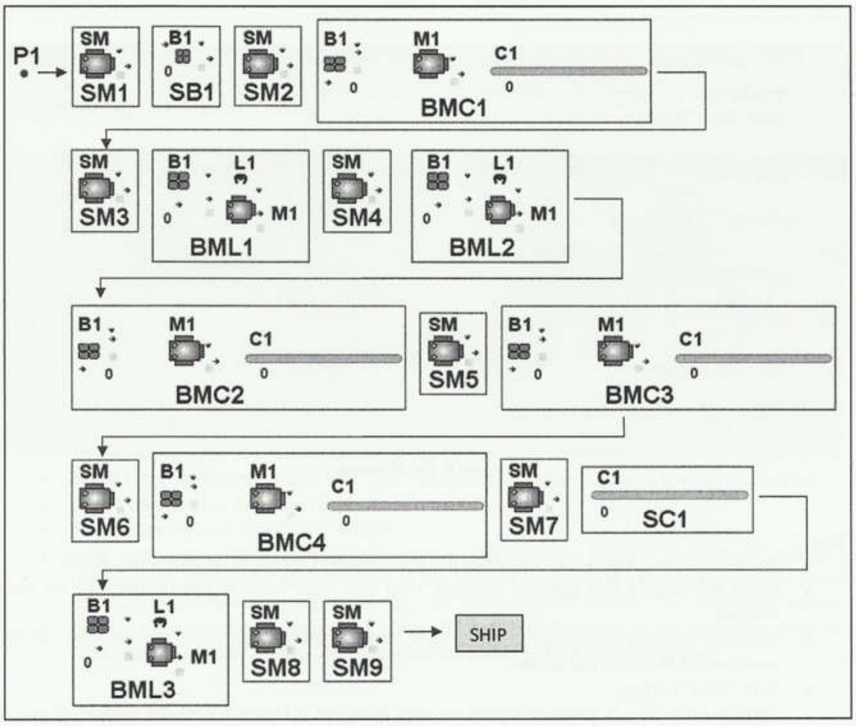

Figure 7: Layout

8

Table 3: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Step 1:

- Please select "Assembly line" from the list of layouts as shown in Figure 8.
- Click "Next" button

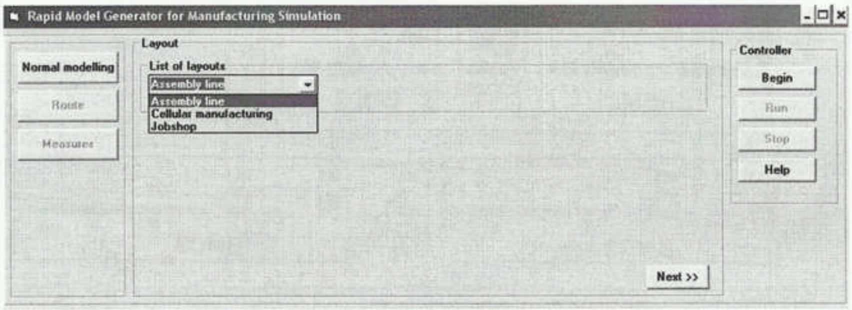

Figure 8: List of layout

Step 2:

- Please select the modules and quantity of each module as shown in Figure 9 and Table 4.
- Select the module and quantity required, then click "Add" button. Repeat this step for each module.
- When all modules have been selected, click "Begin" button, then "Run" button. Now, all the modules are shown in the screen.
- Click "Stop" button.
- Position each module based on layout required as shown in Figure 7. Click the module, drag and drop. Then, click "Next" button to link the elements (route for the part).

Table 4: Data for modules and its quantity

Module	Quantity
P (Part)	1
SM (Single machine)	9
SB (Single buffer)	1
SC (Single conveyor)	1
BMC (Buffer machine conveyor)	4
BML (Buffer machine labour)	3

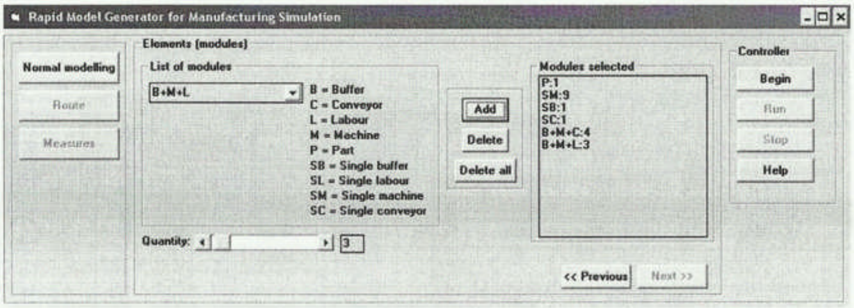

Figure 9: Modules and quantity

Step 3:

- Please add route for the part as shown in Figure 10.
- Select the first destination and click "Add" button. Repeat this step until the last destination.
- Click "Next" button and "Run" button.
- To stop the process, click "Stop" button
- Now, run the simulation model with run time at 480 unit time. Click the "Start RunAt" option on the "Execute Action Bar" at the bottom of the Witness screen. In the text box, enter the time as 480. Switch OFF the walk speed by clicking the "Walk ON/OFF" button. Then click "Run" button.
- To start again the simulation process at time 0, click "Begin" button on the prototype, then click "Run" button on the "Execute Action Bar" at the bottom of the Witness screen.

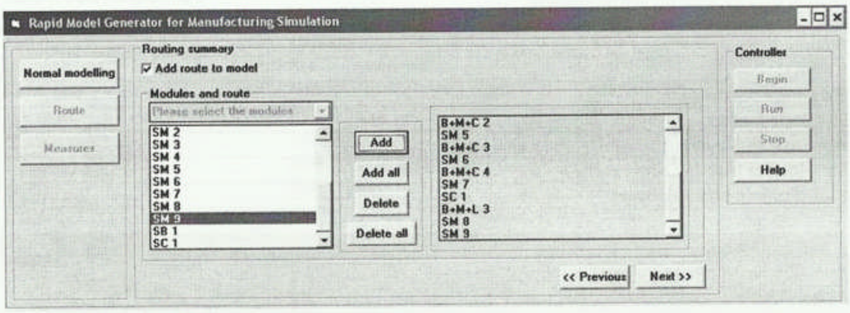

Figure 10: Routing

Evaluation: Exercise 1

	Difficult					Easy
Exercise 1	1	2	3	4	5	6

Exercise 2: Changing the routing (Route)

Exercise 2(a): Amend the previous model with the following layout (Figure 11). Link the modules and run the model.

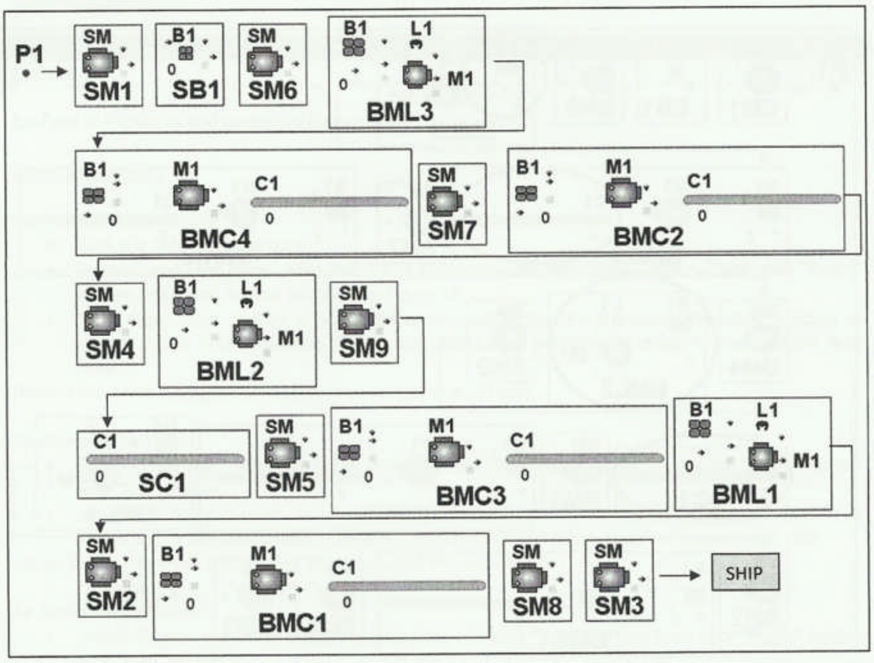

Figure 11: New layout

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 12.

Step 1:

- Click the "Route" button.
- The current route is shown in left panel. Click "Add all" button and the current route is now available in the right panel (New Route) as shown in Figure 13.
- On the "New Route" panel, select the element B1 in the "BML3" module, and click "Delete". Repeat this step for element C1 in module "BMC4". Then delete all elements in module "BML2" and module "SC1". Then click "Begin" button and "Run" button.

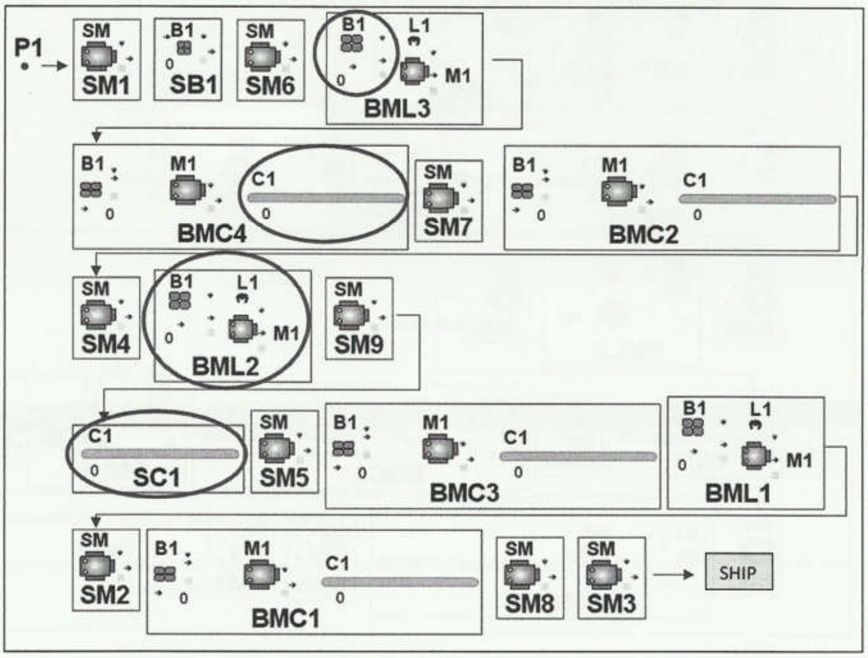

Figure 12: Changing the route

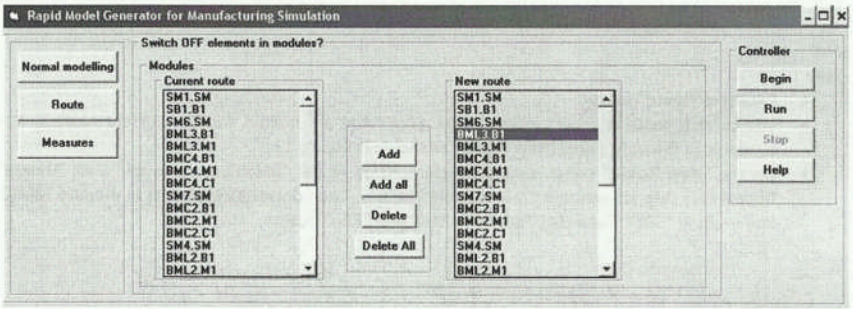

Figure 13: Switching ON/OFF elements in modules

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures (Measures)

General guidelines

To measure the lead time:

- Click the "Measures" button.
- Select "Long lead time" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button as shown in Figure 14.
- Now, click "Stop" button. A histogram is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the lead time.

(Note: Please use histogram to display the average of lead time).

To measure the WIP:

- Select "High WIP" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button.
- Now, click "Stop" button. A timeseries is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the WIP.

(Note: Please use timeseries to plot the number of WIP over time)

To detect the bottleneck:

- Select "Bottleneck" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button
- Now, click "Stop" button. Three pie charts are provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the machine utilisation.

(Note: Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

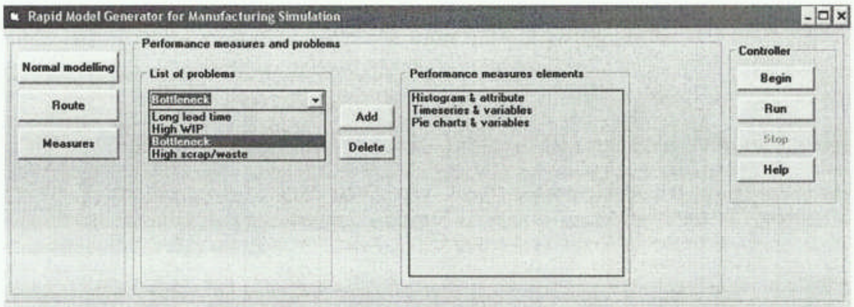

Figure 14: Measures

14

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 15.

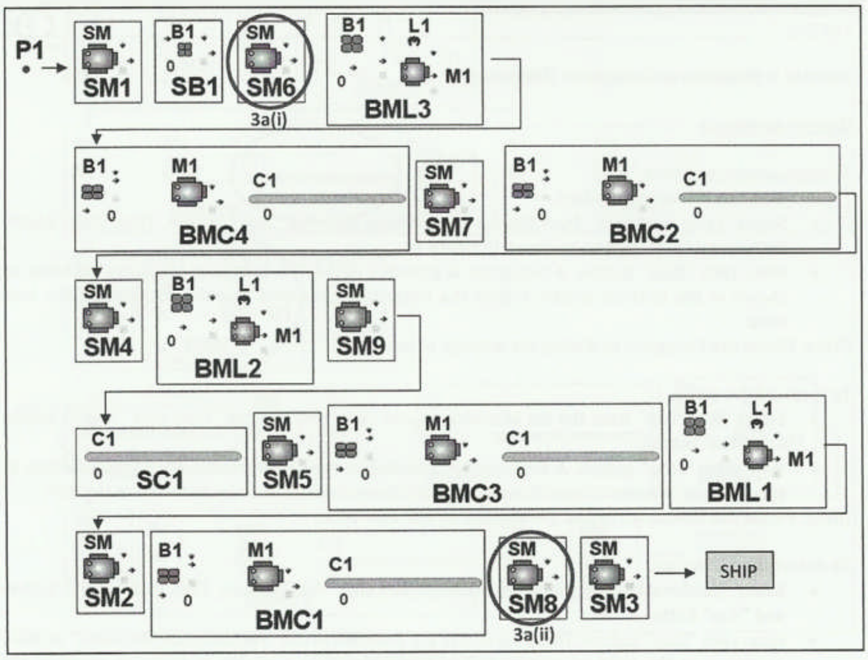

Figure 15: Exercise 3a

In order to include the breakdown in both machines, it is necessary to specify that breakdown will occur in the element (machine) details as shown in Figure 16.

15

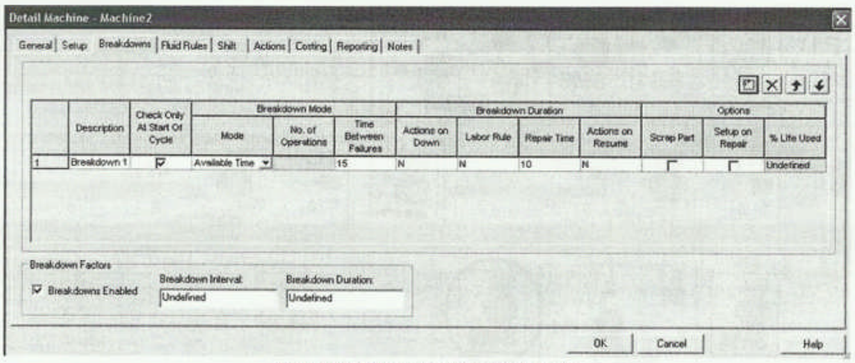

Figure 16: Data for machine breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?	90.4.	96.3
Number of WIP (work-in-progress)?	169.	175.
What is the average of machine utilisation?	33.02.	31.87.

Evaluation: Exercise 3(a)

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

Exercise 3b: Comparing the effect of machine reliability (breakdown) for SM9 as shown in Figure 17 based on two conditions:

16

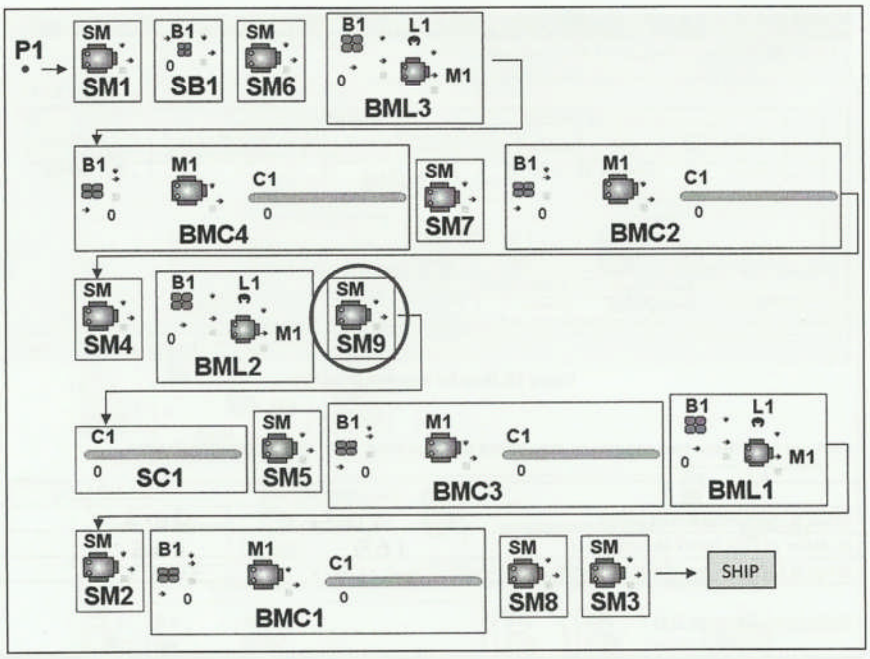

Figure 17: Exercise 3b

i. breakdown is often (short MTBF[3]) but repair time is quick (short MTTF[4])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[3] MTBF: Mean time between failures

[4] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?	20.28	191
Number of WIP (work-in-progress)?	20	401
What is the average of machine utilisation?	48.21.	8.33.

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

Kevin 17/8/10

The purpose of these questions is to measure to what extend this prototype can help the user to build the model. Please circle the number between 1 – 5, 1 being Strongly Disagree and 5 being Strongly Agree.

1. **User experience**

How long have you been involved in simulation and model building area?

Never	0 – 6 month	7 – 12 month	More than 12 month	No longer
			✓	

2. **Usage of Witness software (please tick)**

During lectures only	
During group project	
During thesis project	✓
Before I came to Cranfield University	✓

3. **Ease of use**

	Strongly Disagree					Strongly Agree
The prototype is easy to use	1	2	3	4	5	6
The instructions are easy to read and understandable	1	2	3	4	5	6

4. **Usefulness**

	Strongly Disagree					Strongly Agree
The prototype will help me in model building	1	2	3	4	5	6
The prototype will help reduce time for model building	1	2	3	4	5	6
I can create the physical elements easily and faster	1	2	3	4	5	6
I can link the elements and run the model easily	1	2	3	4	5	6
I can switch ON/OFF any elements, link them again and run the model easily	1	2	3	4	5	6
I can easily measure the performance of the system (throughput rate, WIP, etc.)	1	2	3	4	5	6
All the elements provided for the performance measures are useful	1	2	3	4	5	6
The prototype has a lot of potential in improving model building	1	2	3	4	5	6
I will recommend this prototype to my colleagues	1	2	3	4	5	6

19

5. Visual appearance

	Strongly Disagree					Strongly Agree
The prototype displays visually pleasing design	1	2	3	4	5	6
Graphics and colour detract from actual content	1	2	3	4	5	6
The icons of the elements are easy to understand	1	2	3	4	5	6

6. Comments/suggestions

Appendix L Testing and validation results (Participant 8)

NADIAH ABDUL RAHMAN.

25/11/10
Khamis
10-12

START - 10.35 AM
STOP - 11.17 AM

Rapid Model Generator for Manufacturing Simulation

Aim: To investigate a new method to rapidly build simulation model based on classification of problems using cladistics technique and template approach.

This exercise is part of the study in developing a prototype referred to as "Rapid Model Generator" in simulation modelling. Your participation in this study will help us improve the design of the prototype.

We would appreciate if you could give us your true opinion and suggestions about the prototype. Please note that we are evaluating the prototype, NOT your performance in using the software. The intention is to measure to what extent the prototype can help the user build the model.

Mode A: Building a model manually

Exercise 1: Building, linking and running a model

Please build a model as shown on Figure 1. Linking all the elements and run the model. A part is delivered to Machine1 and other elements as shown below.

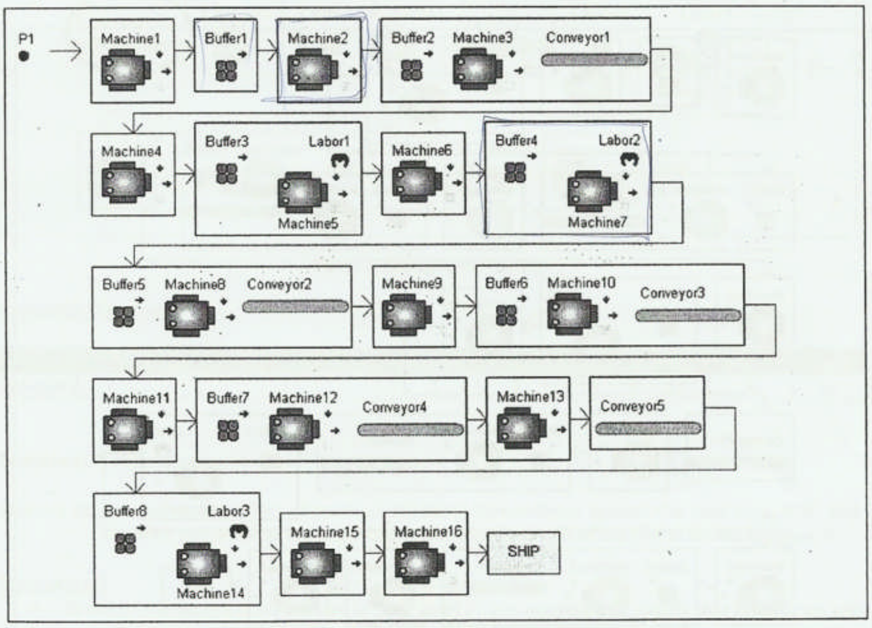

Figure 1: Layout

1

Table 1: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Evaluation: Exercise 1

	Difficult					Easy
Exercise 1	1	2	3	4	5	6

Exercise 2: Changing the routing

start 11:20 AM   Stop 11:49 AM

Exercise 2(a): Amend the previous model with the following layout (Figure 2). Link the elements and run the model.

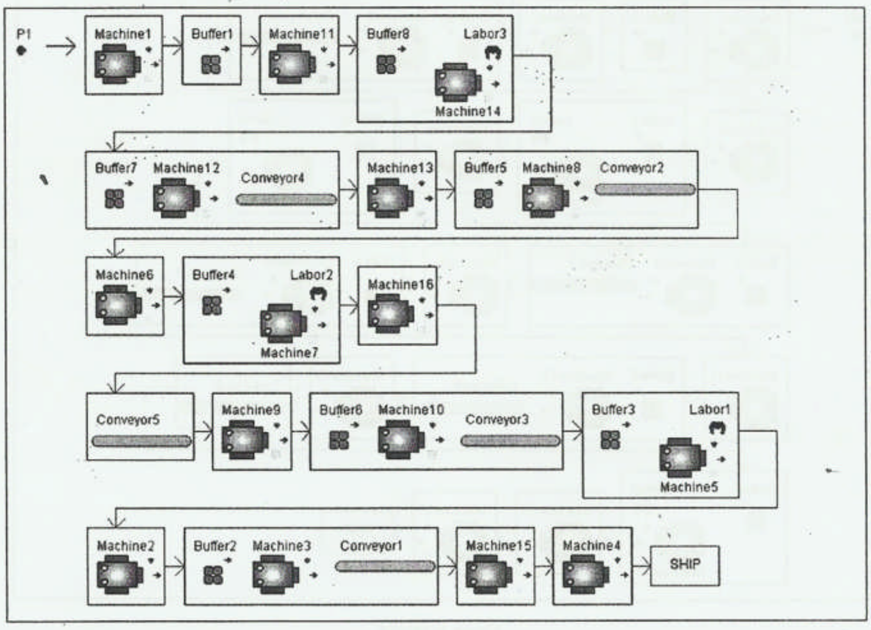

Figure 2: New layout

2

START 11.49 STOP 1.59

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 3.

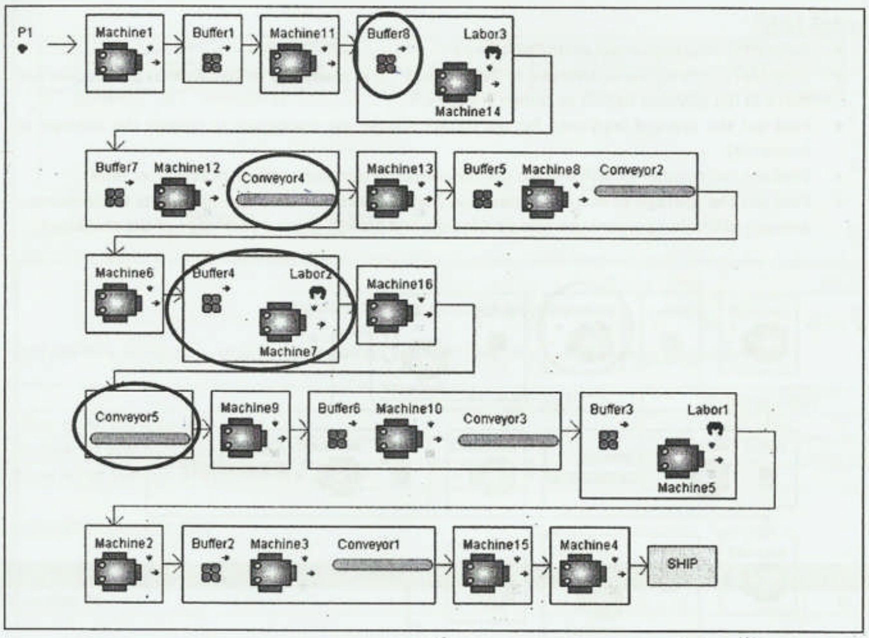

Figure 3: Changing the routing

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures X START 12.00 AM - CAN COMPLETED

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 4.

Exercise 3a(i)

- In order to include the breakdown in "Machine11", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).

- Find out the average of machine utilisation ("Machine11") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3a(ii)

- Delete the breakdown details in "Machine11".
- In order to include the breakdown in "Machine15", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine15") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

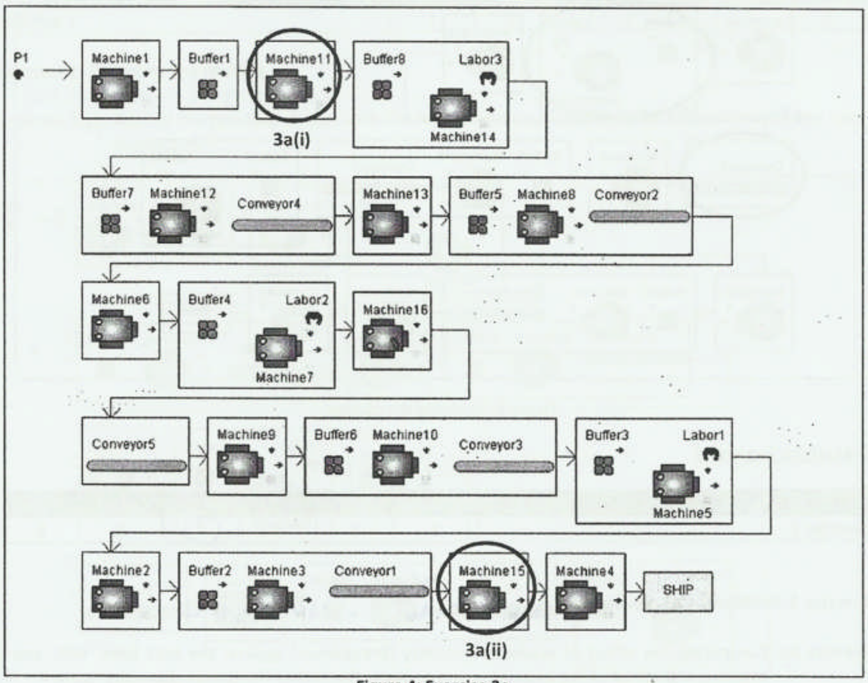

Figure 4: Exercise 3a

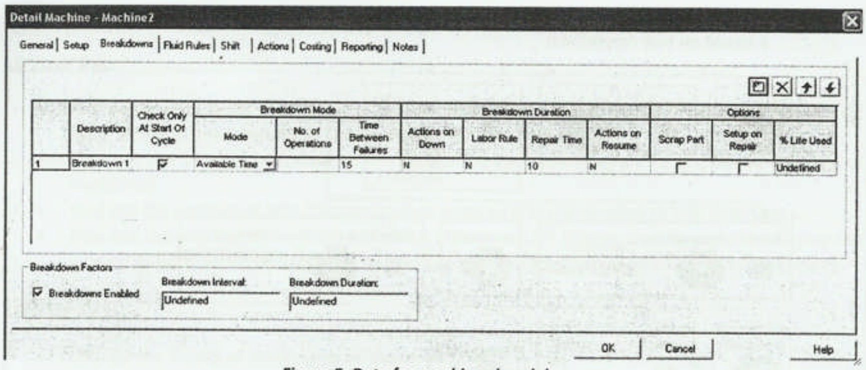

Figure 5: Data for machines breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

Evaluation: Exercise 3(a)

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

Exercise 3b: Comparing the effect of machine reliability (breakdown) for Machine16 as shown in Figure 6 based on two conditions:

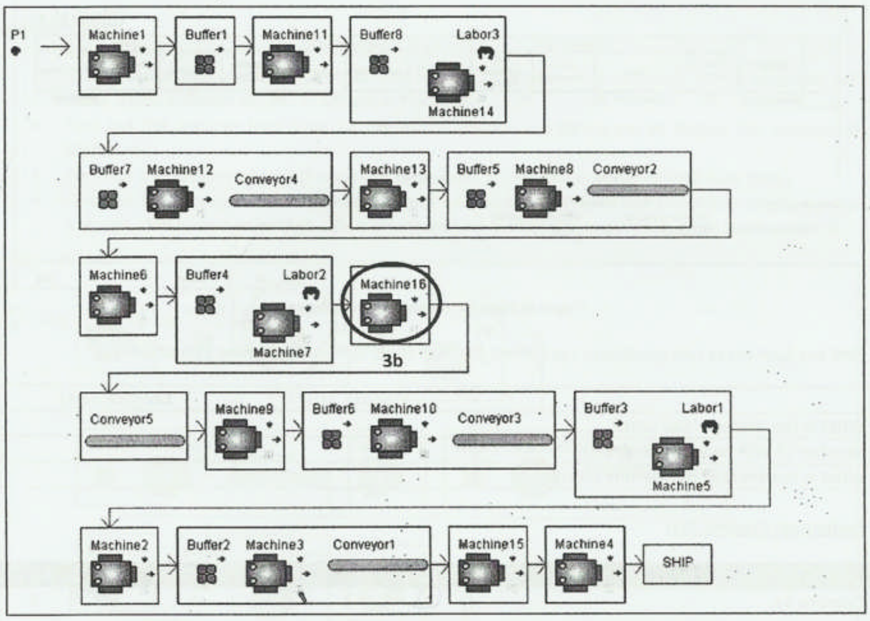

Figure 6: Exercise 3b

Table 2: Data for Exercise 3b

i. breakdown is often (short MTBF[1]) but repair time is quick (short MTTF[2])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[1] MTBF: Mean time between failures

[2] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

Exercise 3b(i)

- In order to include the breakdown in "Machine16", it is necessary to specify that breakdown will occur in the element details as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3b(ii)

- Change the details of breakdown as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

NADIAH ABDUL RAHMAN

START 12.30 AM
Stop 12.41

Mode B: Building the model using prototype

Please follow the guidelines and instructions provided for each exercise.

Exercise 1: Building, linking and running a model (Normal Modelling)

Please build a model as shown on Figure 7. Linking all the elements and run the model. A part is delivered to SM1 and other elements as shown below.

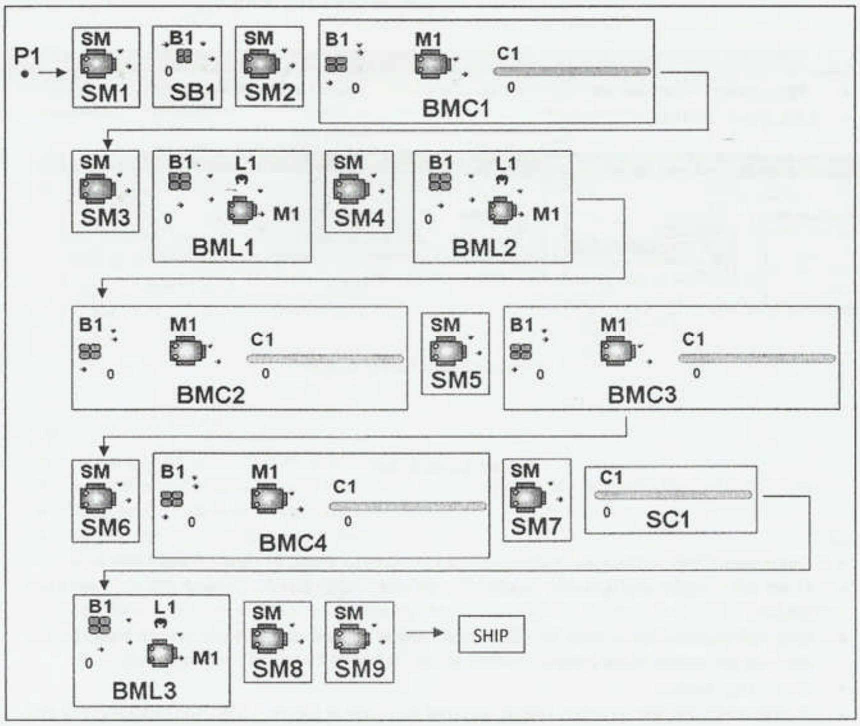

Figure 7: Layout

Table 3: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Step 1:

- Please select "Assembly line" from the list of layouts as shown in Figure 8.
- Click "Next" button

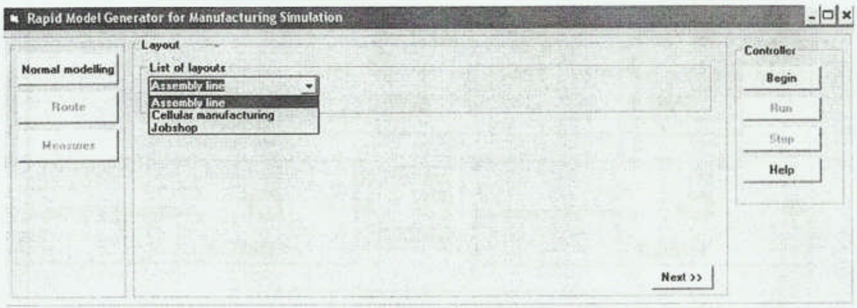

Figure 8: List of layout

Step 2:

- Please select the modules and quantity of each module as shown in Figure 9 and Table 4.
- Select the module and quantity required, then click "Add" button. Repeat this step for each module.
- When all modules have been selected, click "Begin" button, then "Run" button. Now, all the modules are shown in the screen.
- Click "Stop" button.
- Position each module based on layout required as shown in Figure 7. Click the module, drag and drop. Then, click "Next" button to link the elements (route for the part).

Table 4: Data for modules and its quantity

Module	Quantity
P (Part)	1
SM (Single machine)	9
SB (Single buffer)	1
SC (Single conveyor)	1
BMC (Buffer machine conveyor)	4
BML (Buffer machine labour)	3

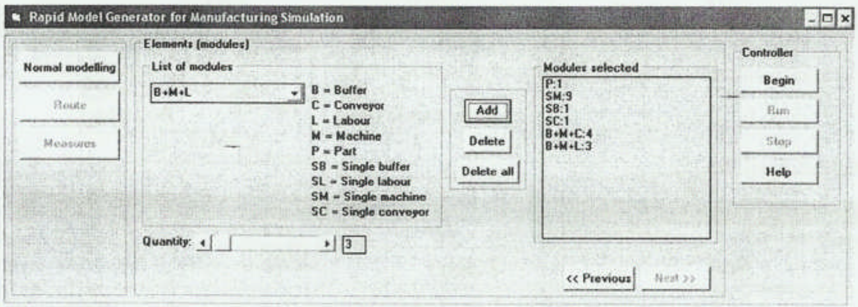

Figure 9: Modules and quantity

Step 3:

- Please add route for the part as shown in Figure 10.
- Select the first destination and click "Add" button. Repeat this step until the last destination.
- Click "Next" button and "Run" button.
- To stop the process, click "Stop" button
- Now, run the simulation model with run time at 480 unit time. Click the "Start RunAt" option on the "Execute Action Bar" at the bottom of the Witness screen. In the text box, enter the time as 480. Switch OFF the walk speed by clicking the "Walk ON/OFF" button. Then click "Run" button.
- To start again the simulation process at time 0, click "Begin" button on the prototype, then click "Run" button on the "Execute Action Bar" at the bottom of the Witness screen.

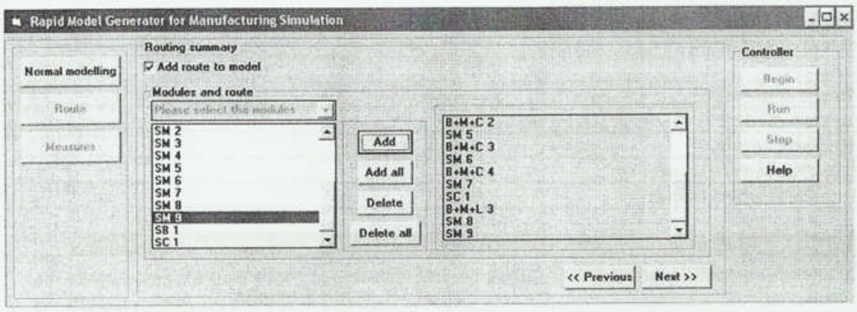

Figure 10: Routing

Evaluation: Exercise 1

	Difficult					Easy
Exercise 1	1	2	3	4	5	6

Exercise 2: Changing the routing (Route)

Exercise 2(a): Amend the previous model with the following layout (Figure 11). Link the modules and run the model.

Start 12.42AM

END 12.47AM

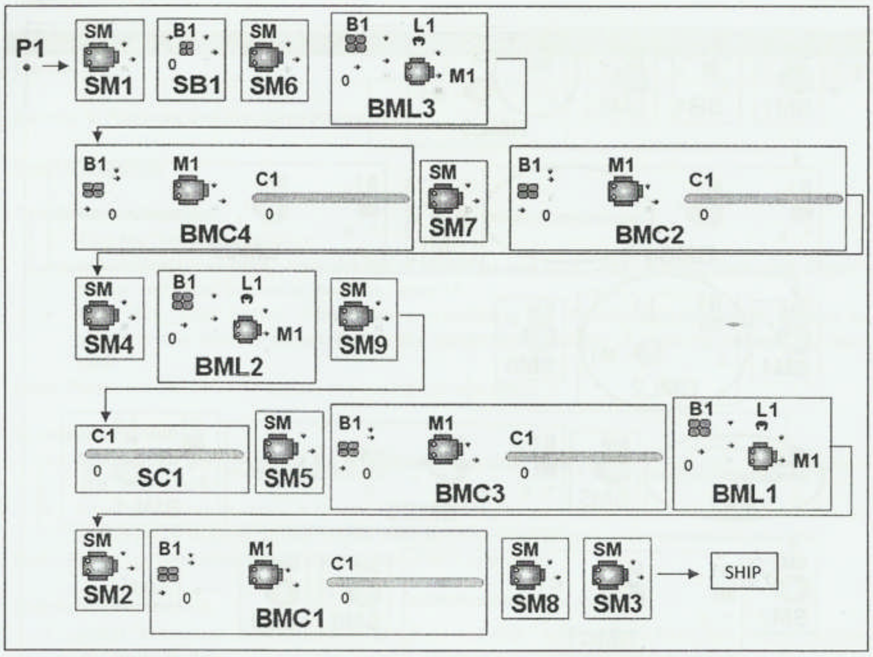

Figure 11: New layout

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 12.

Step 1:

- Click the "Route" button.
- The current route is shown in left panel. Click "Add all" button and the current route is now available in the right panel (New Route) as shown in Figure 13.
- On the "New Route" panel, select the element B1 in the "BML3" module, and click "Delete". Repeat this step for element C1 in module "BMC4". Then delete all elements in module "BML2" and module "SC1". Then click "Begin" button and "Run" button.

Star 12.48
stop 12.50

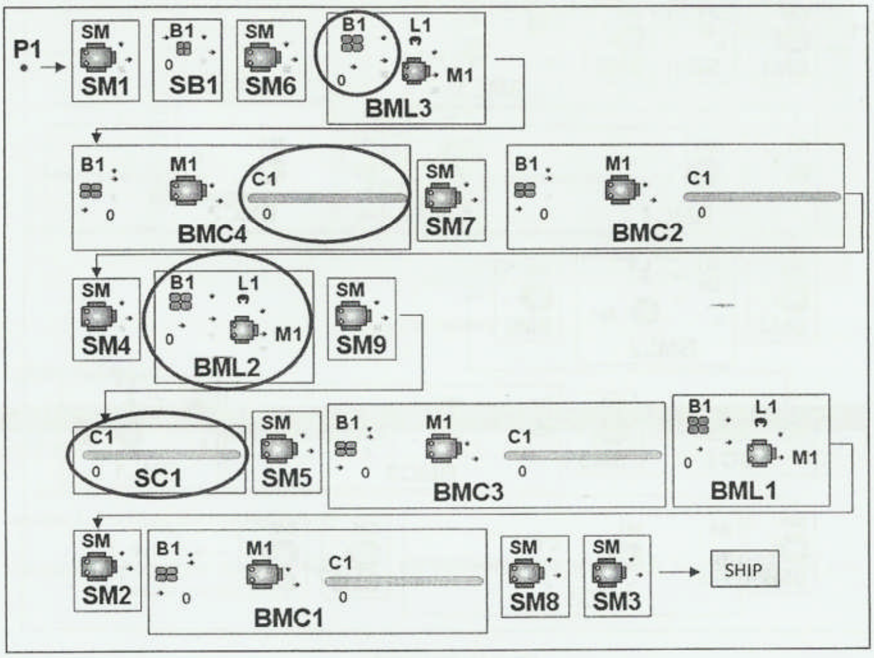

Figure 12: Changing the route

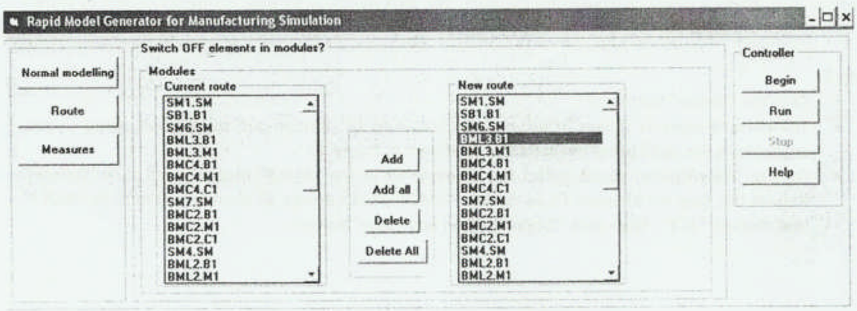

Figure 13: Switching ON/OFF elements in modules

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures (Measures)

General guidelines

To measure the lead time:

- Click the "Measures" button.
- Select "Long lead time" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button as shown in Figure 14.
- Now, click "Stop" button. A histogram is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the lead time.

(Note: Please use histogram to display the average of lead time).

To measure the WIP:

- Select "High WIP" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button.
- Now, click "Stop" button. A timeseries is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the WIP.

(Note: Please use timeseries to plot the number of WIP over time)

To detect the bottleneck:

- Select "Bottleneck" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button
- Now, click "Stop" button. Three pie charts are provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the machine utilisation.

(Note: Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

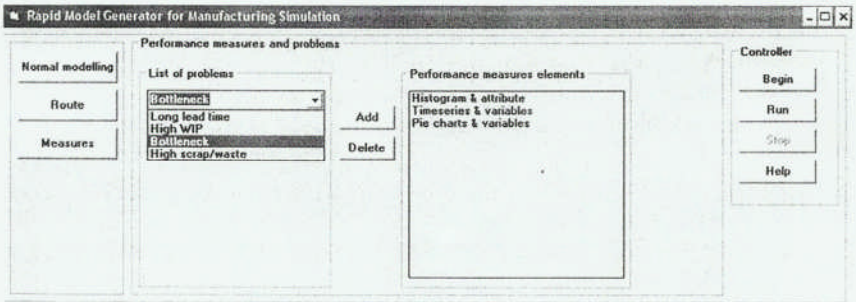

Figure 14: Measures

Start 12.52
Stop 12.56

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 15.

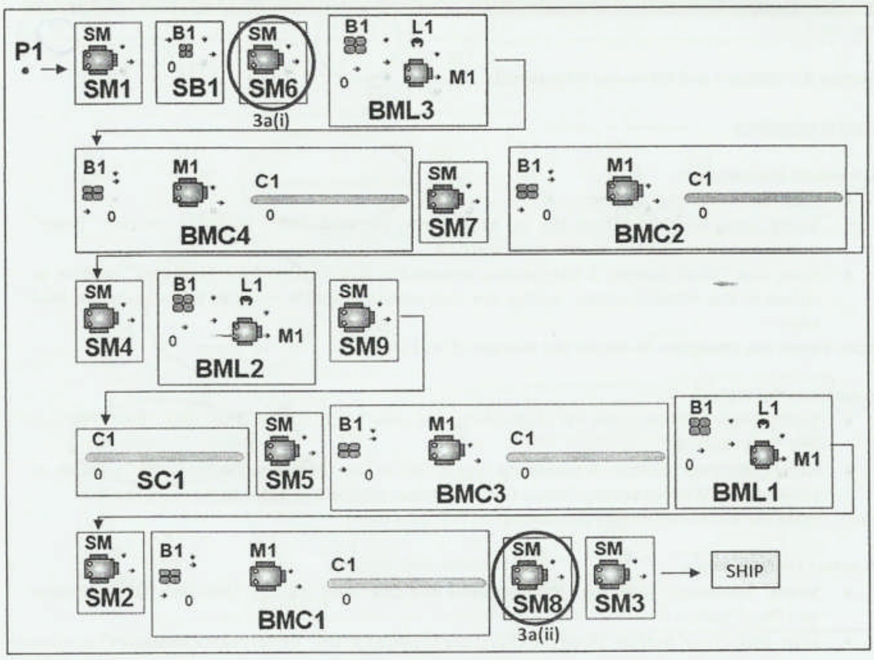

Figure 15: Exercise 3a

In order to include the breakdown in both machines, it is necessary to specify that breakdown will occur in the element (machine) details as shown in Figure 16.

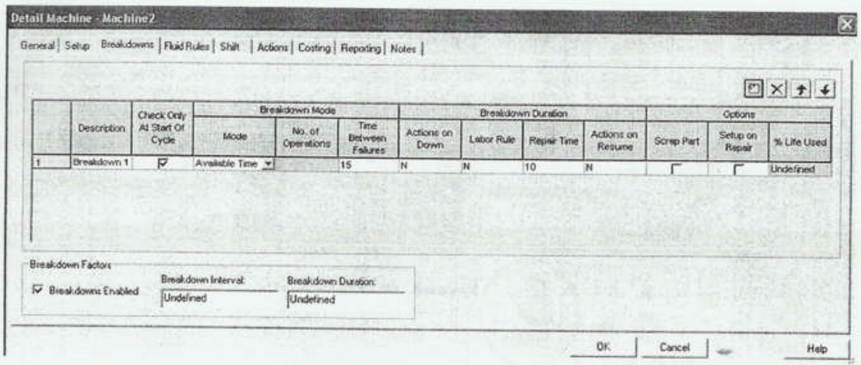

Figure 16: Data for machine breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

START 1-07

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?	90·40	96·31
Number of WIP (work-in-progress)?	169	175
What is the average of machine utilisation?	33·02	31 ·87

— FINISH : 1·07 AM FINISH : 1·14AM.

Evaluation: Exercise 3(a)

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

Exercise 3b: Comparing the effect of machine reliability (breakdown) for SM9 as shown in Figure 17 based on two conditions:

16

~~Start 1:16 AM~~

~~Finish~~

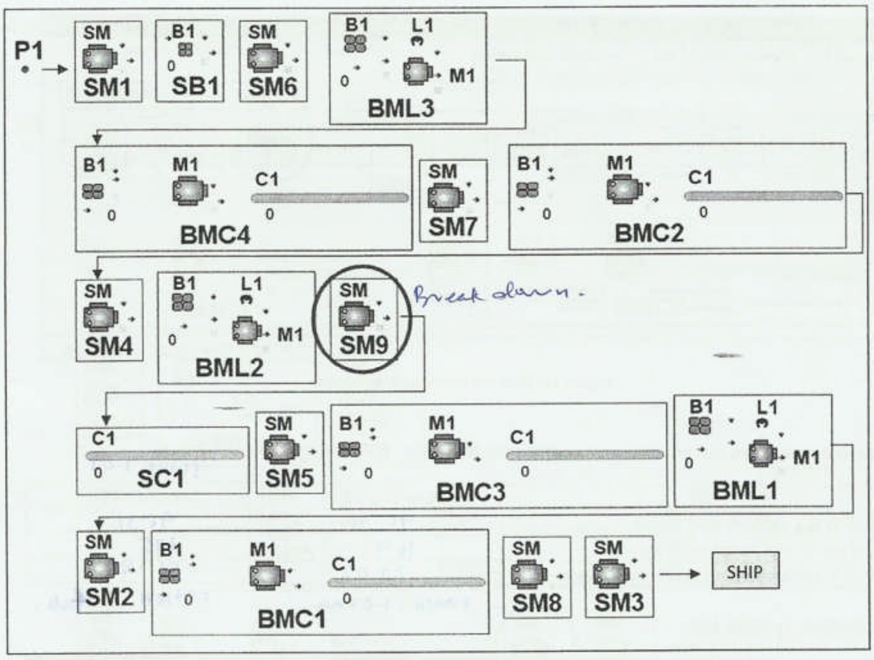

Figure 17: Exercise 3b

~~Start 1:17AM~~

i. breakdown is often (short MTBF[3]) but repair time is quick (short MTTF[4])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[3] MTBF: Mean time between failures

[4] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation. Start 1.21 PM

Start 1.17 PM

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?	20.28.	191.23
Number of WIP (work-in-progress)?	20	401
What is the average of machine utilisation?	48.21	8.33

Finish : 1.21pm

Finish : 1.24pm

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

18

Nadiah

The purpose of these questions is to measure to what extend this prototype can help the user to build the model. Please circle the number between 1 – 5, 1 being Strongly Disagree and 5 being Strongly Agree.

1. **User experience**

How long have you been involved in simulation and model building area?

Never	0 – 6 month	7 – 12 month	More than 12 month	No longer
		✓		

2. **Usage of Witness software (please tick)**

During lectures only	✓
During group project	
During thesis project	
Before I came to Cranfield University	

3. **Ease of use**

	Strongly Disagree					Strongly Agree
The prototype is easy to use	1	2	3	4	5	6
The instructions are easy to read and understandable	1	2	3	4	5	6

4. **Usefulness**

	Strongly Disagree					Strongly Agree
The prototype will help me in model building	1	2	3	4	5	6
The prototype will help reduce time for model building	1	2	3	4	5	6
I can create the physical elements easily and faster	1	2	3	4	5	6
I can link the elements and run the model easily	1	2	3	4	5	6
I can switch ON/OFF any elements, link them again and run the model easily	1	2	3	4	5	6
I can easily measure the performance of the system (throughput rate, WIP, etc.)	1	2	3	4	5	6
All the elements provided for the performance measures are useful	1	2	3	4	5	6
The prototype has a lot of potential in improving model building	1	2	3	4	5	6
I will recommend this prototype to my colleagues	1	2	3	4	5	6

5. Visual appearance

	Strongly Disagree					Strongly Agree
The prototype displays visually pleasing design	1	2	3	4	5	6
Graphics and colour detract from actual content	1	2	3	4	5	6
The icons of the elements are easy to understand	1	2	3	4	5	6

6. Comments/suggestions

IT WILL HELPS STUDENT TO DEVELOP MODEL + REDUCE TIME.

20

Appendix M Testing and validation results (Participant 9)

Aricko Khena K.
25/11/10
Khamis 10-12

Rapid Model Generator for Manufacturing Simulation

Aim: To investigate a new method to rapidly build simulation model based on classification of problems using cladistics technique and template approach.

This exercise is part of the study in developing a prototype referred to as "Rapid Model Generator" in simulation modelling. Your participation in this study will help us improve the design of the prototype.

We would appreciate if you could give us your true opinion and suggestions about the prototype. Please note that we are evaluating the prototype, NOT your performance in using the software. The intention is to measure to what extent the prototype can help the user build the model.

Mode A: Building a model manually

Exercise 1: Building, linking and running a model 10.37. – 11.04.

Please build a model as shown on Figure 1. Linking all the elements and run the model. A part is delivered to Machine1 and other elements as shown below.

0.5 0.5 L=10. C=10 J=0.1

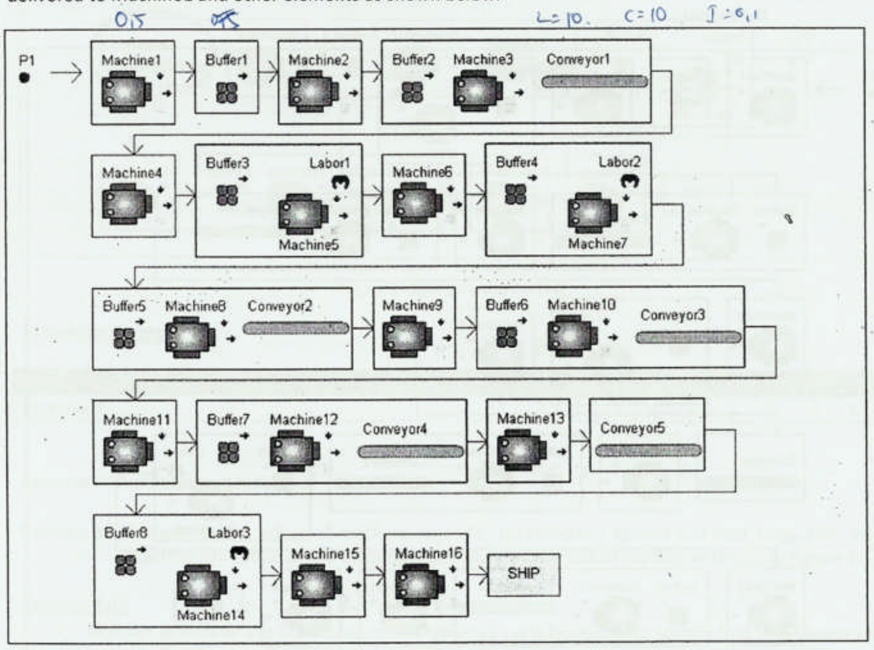

Figure 1: Layout

1

Table 1: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Evaluation: Exercise 1

	Difficult					Easy
Exercise 1	1	2	3	4	5	6

Exercise 2: Changing the routing

11.08

Exercise 2(a): Amend the previous model with the following layout (Figure 2). Link the elements and run the model.

11.41

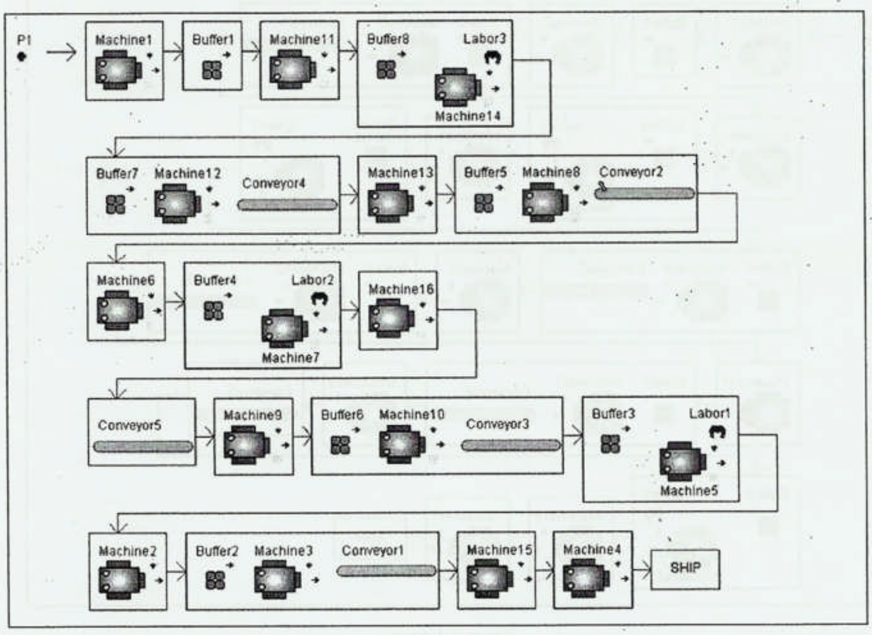

Figure 2: New layout

11.42.
11.45.

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 3.

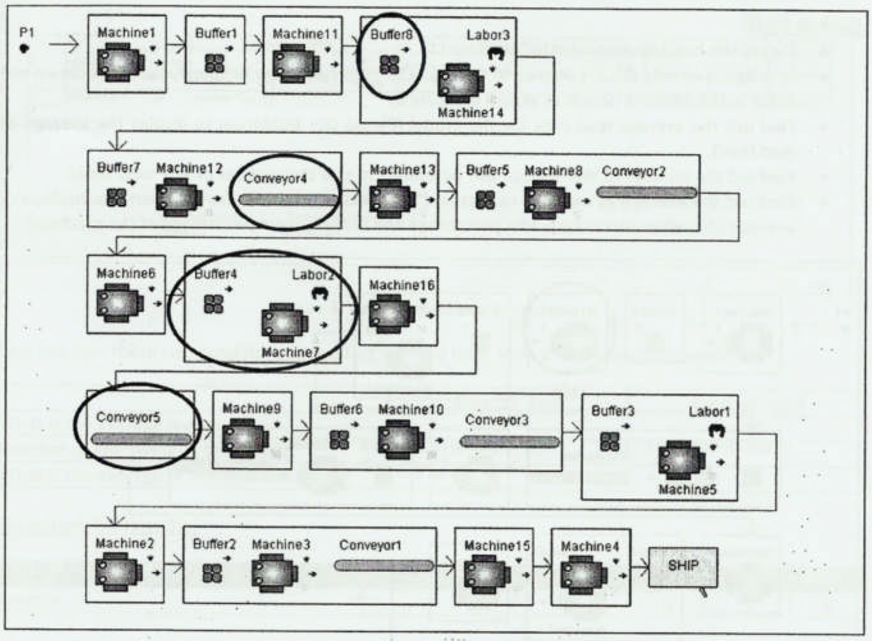

Figure 3: Changing the routing

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

11.48.

Exercise 3: Problems and measures

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 4.

Exercise 3a(i)

- In order to include the breakdown in "Machine11", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).

can't completed.

- Find out the average of machine utilisation ("Machine11") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3a(ii)

- Delete the breakdown details in "Machine11".
- In order to include the breakdown in "Machine15", it is necessary to specify that breakdown will occur in the element details as shown in Figure 5.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine15") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

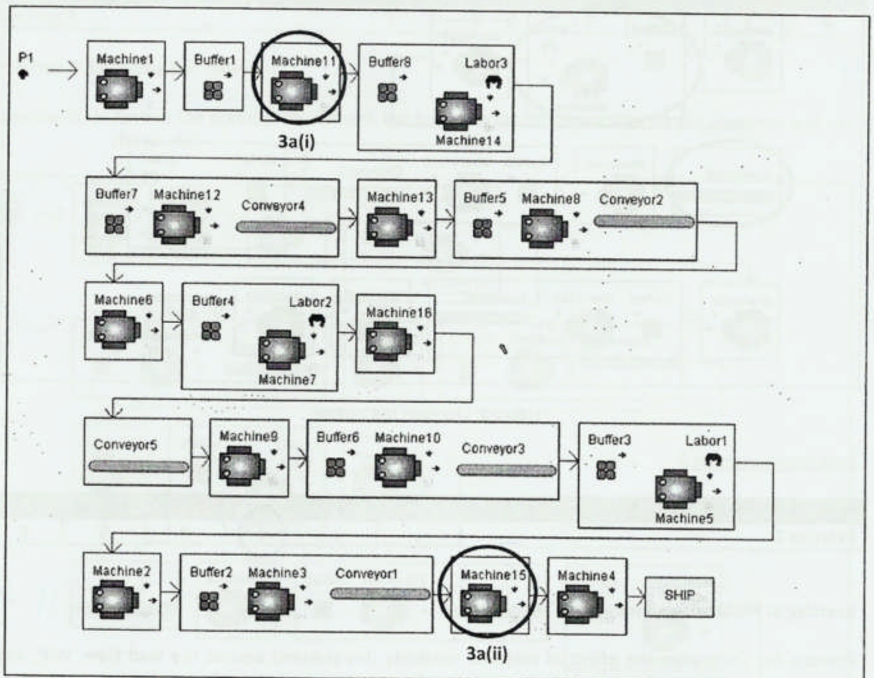

Figure 4: Exercise 3a

4

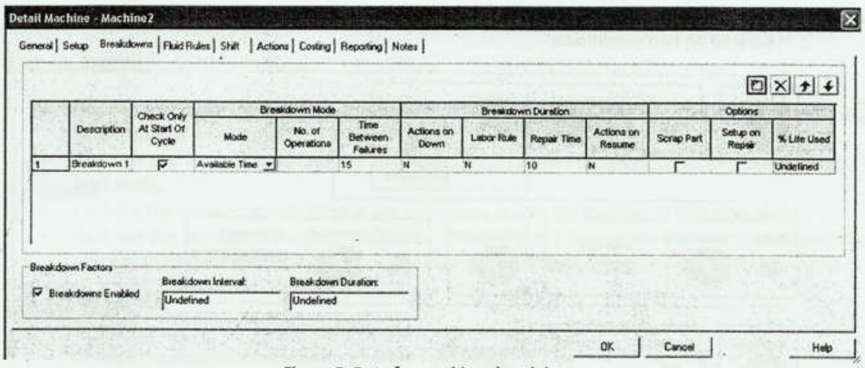

Figure 5: Data for machines breakdown

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

Evaluation: Exercise 3(a)

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

5

Exercise 3b: Comparing the effect of machine reliability (breakdown) for Machine16 as shown in Figure 6 based on two conditions:

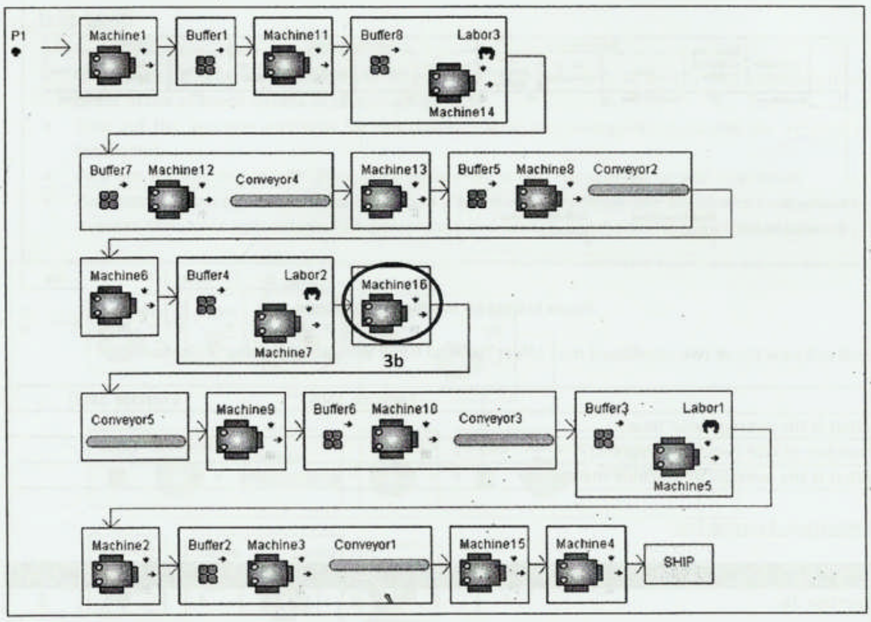

Figure 6: Exercise 3b

Table 2: Data for Exercise 3b

i. breakdown is often (short MTBF[1]) but repair time is quick (short MTTF[2])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[1] MTBF: Mean time between failures

[2] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

Exercise 3b(i)

- In order to include the breakdown in "Machine16", it is necessary to specify that breakdown will occur in the element details as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

Exercise 3b(ii)

- Change the details of breakdown as shown in Table 2.
- Find out the average lead-time for the model (Please use histogram to display the average of lead time).
- Find out the number of WIP (Please use timeseries to plot the number of WIP over time).
- Find out the average of machine utilisation ("Machine16") (Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?		
Number of WIP (work-in-progress)?		
What is the average of machine utilisation?		

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

7

ARKO .K.K

Mode B: Building the model using prototype

Please follow the guidelines and instructions provided for each exercise.

Exercise 1: Building, linking and running a model (Normal Modelling)

Please build a model as shown on Figure 7. Linking all the elements and run the model. A part is delivered to SM1 and other elements as shown below.

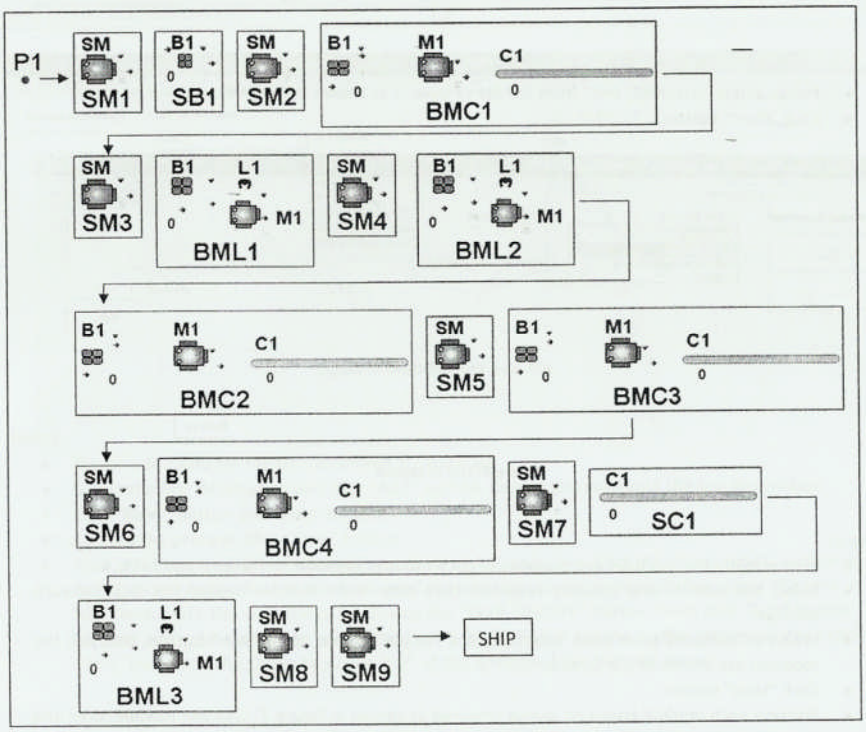

Figure 7: Layout

12:35
12:42.

8

Table 3: Data for Exercise 1

Part	Delivery schedule:	1 every 1 unit time
All machines	Machine cycle time:	0.5 unit time
All buffers	Capacity of buffers:	Default value
The model	Run time:	480 unit time
All conveyors	Length part:	10
	Maximum capacity:	10
	Index time:	0.1

Step 1:

- Please select "Assembly line" from the list of layouts as shown in Figure 8.
- Click "Next" button

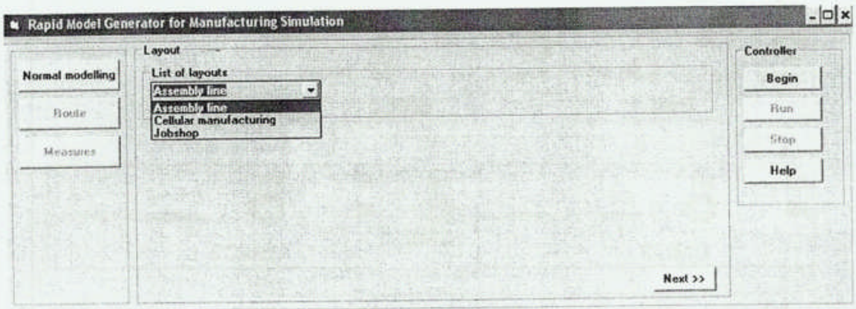

Figure 8: List of layout

Step 2:

- Please select the modules and quantity of each module as shown in Figure 9 and Table 4.
- Select the module and quantity required, then click "Add" button. Repeat this step for each module.
- When all modules have been selected, click "Begin" button, then "Run" button. Now, all the modules are shown in the screen.
- Click "Stop" button.
- Position each module based on layout required as shown in Figure 7. Click the module, drag and drop. Then, click "Next" button to link the elements (route for the part).

Table 4: Data for modules and its quantity

Module	Quantity
P (Part)	1
SM (Single machine)	9
SB (Single buffer)	1
SC (Single conveyor)	1
BMC (Buffer machine conveyor)	4
BML (Buffer machine labour)	3

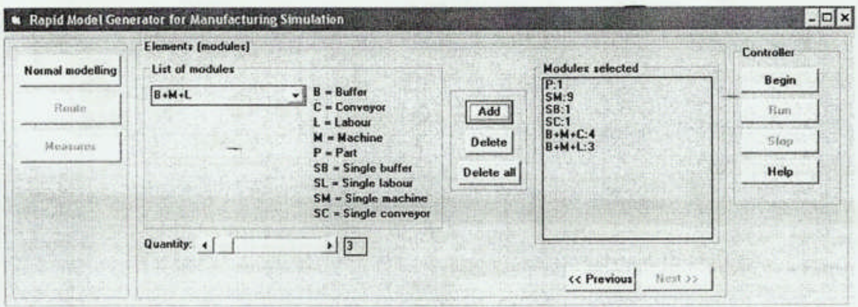

Figure 9: Modules and quantity

Step 3:

- Please add route for the part as shown in Figure 10.
- Select the first destination and click "Add" button. Repeat this step until the last destination.
- Click "Next" button and "Run" button.
- To stop the process, click "Stop" button
- Now, run the simulation model with run time at 480 unit time. Click the "Start RunAt" option on the "Execute Action Bar" at the bottom of the Witness screen. In the text box, enter the time as 480. Switch OFF the walk speed by clicking the "Walk ON/OFF" button. Then click "Run" button.
- To start again the simulation process at time 0, click "Begin" button on the prototype, then click "Run" button on the "Execute Action Bar" at the bottom of the Witness screen.

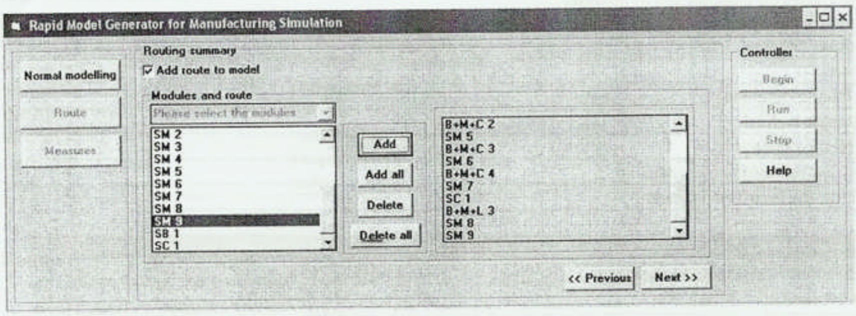

Figure 10: Routing

Evaluation: Exercise 1

	Difficult					Easy
Exercise 1	1	2	3	4	5	6

Exercise 2: Changing the routing (Route)

Exercise 2(a): Amend the previous model with the following layout (Figure 11). Link the modules and run the model.

12:45
12:48

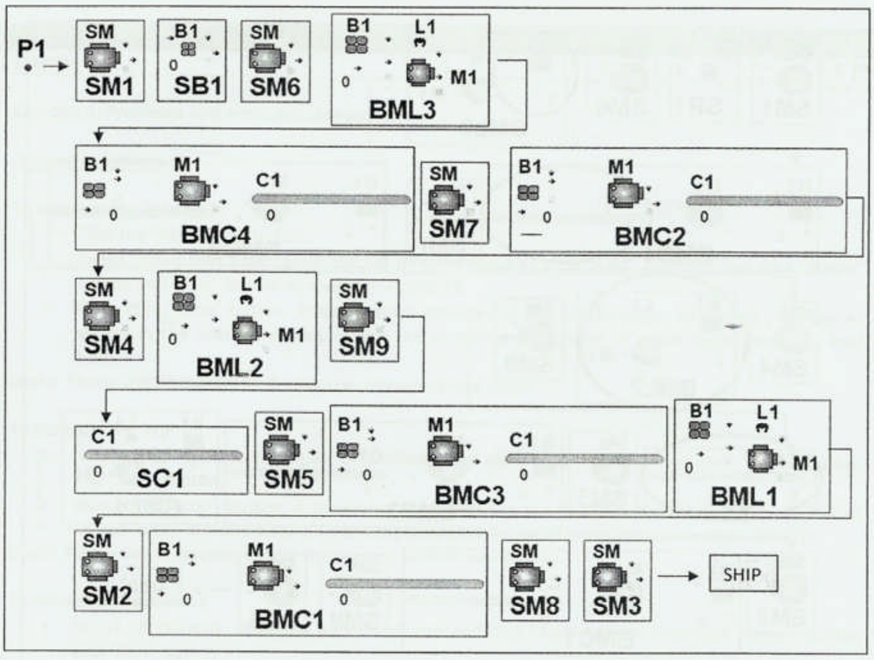

Figure 11: New layout

Exercise 2(b): Make a new link (route) for the part. The part needs to by pass elements circled as shown in Figure 12.

Step 1:

- Click the "Route" button.
- The current route is shown in left panel. Click "Add all" button and the current route is now available in the right panel (New Route) as shown in Figure 13.
- On the "New Route" panel, select the element B1 in the "BML3" module, and click "Delete". Repeat this step for element C1 in module "BMC4". Then delete all elements in module "BML2" and module "SC1". Then click "Begin" button and "Run" button.

12:50
12:51

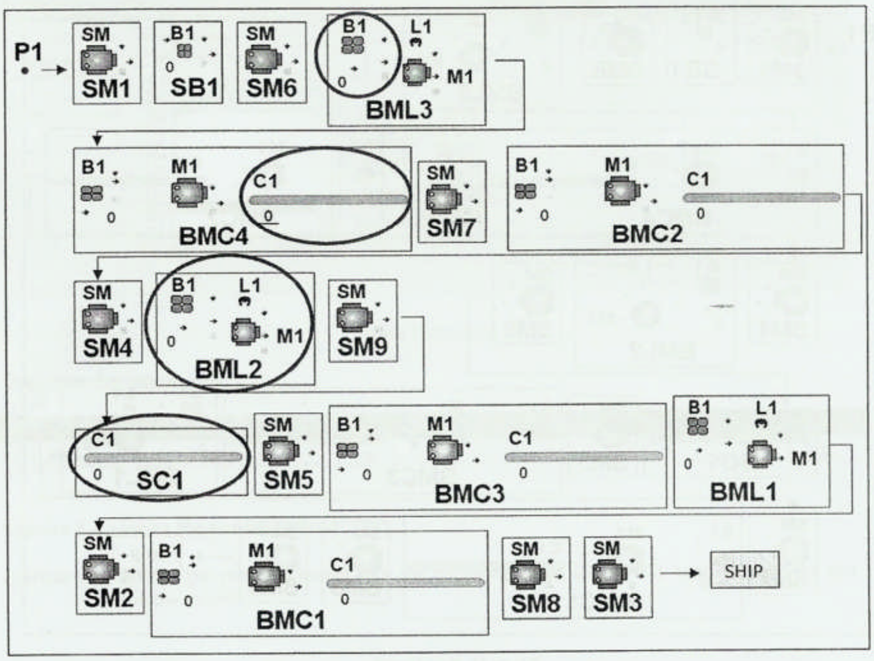

Figure 12: Changing the route

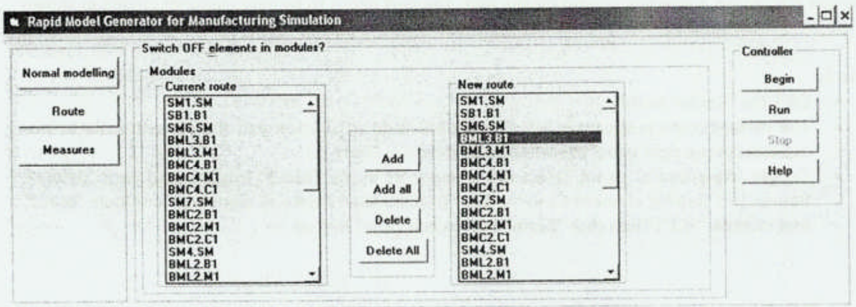

Figure 13: Switching ON/OFF elements in modules

13

Evaluation: Exercise 2

	Difficult					Easy
Exercise 2	1	2	3	4	5	6

Exercise 3: Problems and measures (Measures)

12 : 52

General guidelines

13 : 07

To measure the lead time:

- Click the "Measures" button.
- Select "Long lead time" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button as shown in Figure 14.
- Now, click "Stop" button. A histogram is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the lead time.

(Note: Please use histogram to display the average of lead time).

To measure the WIP:

- Select "High WIP" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button.
- Now, click "Stop" button. A timeseries is provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the WIP.

(Note: Please use timeseries to plot the number of WIP over time)

To detect the bottleneck:

- Select "Bottleneck" from the list of problems and click "Add" button. Then click "Begin" button and "Run" button
- Now, click "Stop" button. Three pie charts are provided in the "Performance Measures" window as shown in the Witness screen. Follow the instructions available in order to measure the machine utilisation.

(Note: Please use pie charts to display the average utilisation percentage, idle percentage and broken down percentage of the machine).

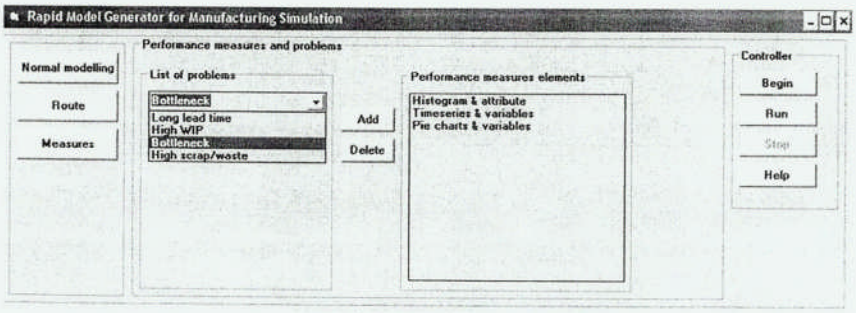

Figure 14: Measures

14

Exercise 3a: Comparing the effect of machine reliability (breakdown) against the lead time, WIP, and machine utilisation at the beginning and towards the end of the line as shown in Figure 15.

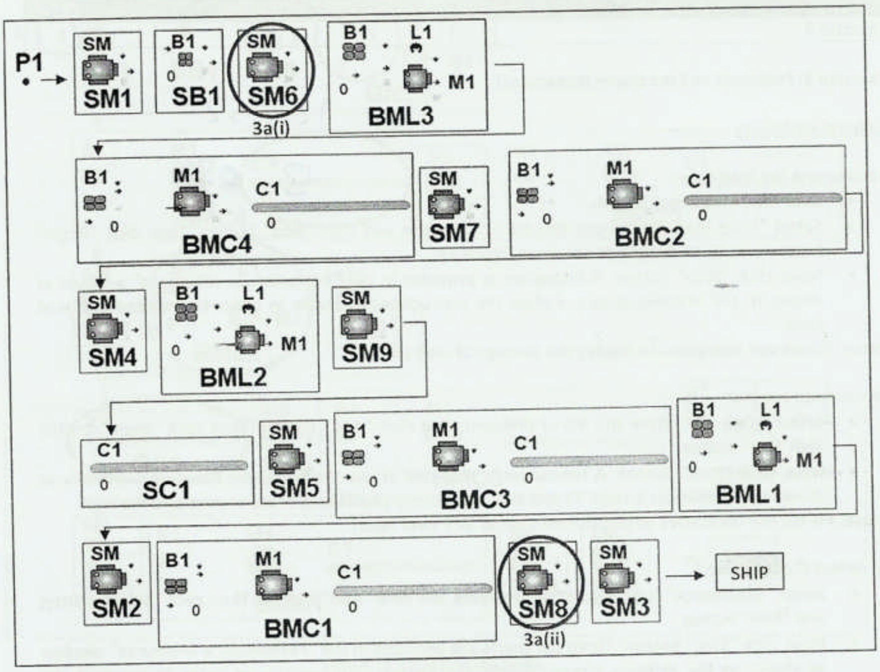

Figure 15: Exercise 3a

In order to include the breakdown in both machines, it is necessary to specify that breakdown will occur in the element (machine) details as shown in Figure 16.

15

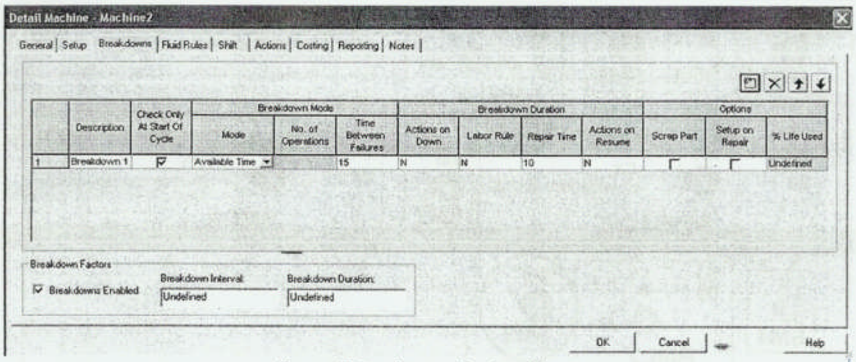

Figure 16: Data for machine breakdown

1:09

1:16.

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3a(i)	Exercise 3a(ii)
What is the average lead time?	90,4	96,31
Number of WIP (work-in-progress)?	169	175
What is the average of machine utilisation?	33,02.	21,87.

Evaluation: Exercise 3(a)

	Difficult					Easy
Exercise 3a	1	2	3	4	5	6

Exercise 3b: Comparing the effect of machine reliability (breakdown) for SM9 as shown in Figure 17 based on two conditions:

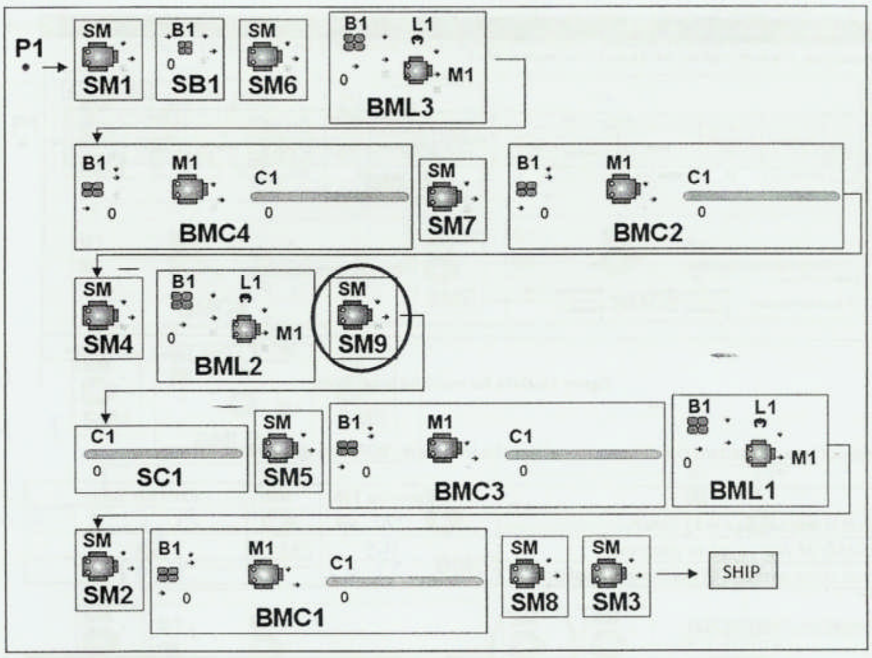

Figure 17: Exercise 3b

1 : 18
1 : 23.

i. breakdown is often (short MTBF[3]) but repair time is quick (short MTTF[4])

Time between failures (MTBF):	1 every 10 unit time
Repair time (MTTF):	1 every 5 unit time

ii. breakdown is not often (long MTBF) and the repair time is long (long MTTF)

Time between failures (MTBF):	1 every 25 unit time
Repair time (MTTF):	1 every 23 unit time

[3] MTBF: Mean time between failures

[4] MTTF: Mean time to failure

Find out how these two conditions may affect the lead time, WIP, and machine utilisation.

	Exercise 3b(i)	Exercise 3b(ii)
What is the average lead time?	20,28	19,
Number of WIP (work-in-progress)?	20	401
What is the average of machine utilisation?	48,21	89,90

Evaluation: Exercise 3(b)

	Difficult					Easy
Exercise 3b	1	2	3	4	5	6

1:23.
1:25

18

Aricko

The purpose of these questions is to measure to what extend this prototype can help the user to build the model. Please circle the number between 1 – 5, 1 being Strongly Disagree and 5 being Strongly Agree.

1. User experience

How long have you been involved in simulation and model building area?

Never	0 – 6 month	7 – 12 month	More than 12 month	No longer
		✓		

2. Usage of Witness software (please tick)

During lectures only	✓
During group project	
During thesis project	✓
Before I came to Cranfield University	

3. Ease of use

	Strongly Disagree					Strongly Agree
The prototype is easy to use	1	2	3	4	5	6
The instructions are easy to read and understandable	1	2	3	4	5	6

4. Usefulness

	Strongly Disagree					Strongly Agree
The prototype will help me in model building	1	2	3	4	5	6
The prototype will help reduce time for model building	1	2	3	4	5	6
I can create the physical elements easily and faster	1	2	3	4	5	6
I can link the elements and run the model easily	1	2	3	4	5	6
I can switch ON/OFF any elements, link them again and run the model easily	1	2	3	4	5	6
I can easily measure the performance of the system (throughput rate, WIP, etc.)	1	2	3	4	5	6
All the elements provided for the performance measures are useful	1	2	3	4	5	6
The prototype has a lot of potential in improving model building	1	2	3	4	5	6
I will recommend this prototype to my colleagues	1	2	3	4	5	6

19

5. **Visual appearance**

	Strongly Disagree					Strongly Agree
The prototype displays visually pleasing design	1	2	3	4	5	6
Graphics and colour detract from actual content	1	2	3	4	5	6
The icons of the elements are easy to understand	1	2	3	4	5	6

6. **Comments/suggestions**

this prototype is really helpful to build a model.

USEFUL !

20